

Performance prediction for oil contaminated carbon dioxide flow boiling heat transfer in a smooth horizontal tube

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It all starts here TM

ABSTRACT

In recent years research into the identification and utilization of natural refrigerants with a low global warming potential, as a working fluid in heat pump cycles, has received much attention. One of these natural refrigerants is carbon dioxide (CO_2). This study investigates correlations used in predicting the convection heat transfer coefficient of CO_2 during flow boiling for both oil contaminated and uncontaminated CO_2 in horizontal smooth tubes and a new correlation is also developed and evaluated.

Various CO_2 specific convection heat transfer correlations were identified from literature. Evaluations performed by Li et al. (2014) indicated that the correlation of Aiyoshizawa et al. (2006) is the most accurate correlation among the six correlations considered in their study. A limitation of the study by Li et al. (2014) is that the correlations were only evaluated for a vapour quality range of 0 to 0.7.

In this study the correlation of Aiyoshizawa et al. (2006) is evaluated over the entire vapour quality range from 0 to 1 using experimental data obtained from the study by Dang et al. (2013). The evaluation showed that 49.27% of the predicted data points fall within a 20% deviation of their corresponding experimental values. It was found that the correlation is inadequate for accurately predicting convection heat transfer coefficients over the entire range of the two-phase flow boiling process, specifically under post-dryout conditions. As a result it was decided to develop a new correlation in this study to improve the flow boiling convection heat transfer coefficient predictions for both oil contaminated and uncontaminated CO_2 in horizontal smooth tubes.

Utilizing the experimental data from Dang et al. (2013), the new correlation was developed to take into consideration the effect of the oil concentration ratio over the entire vapour quality range from 0 to 1. The correlation proposes a new boiling suppression factor, S , and an oil contamination boiling suppression factor, S_{oil} . A new correlation for the dryout vapour quality was also developed in order to improve the prediction accuracy of the post-dryout convection heat transfer coefficients. When evaluated over the entire vapour quality range using the experimental data of Dang et al. (2013), the new correlation predicted 72.20% of the data points within a 20% deviation of their corresponding experimental values. This includes predictions for all calculation conditions, both pre- and post-dryout, with and without oil contamination and for oil concentration ratios ranging from 0% to 5%.

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TABLE OF CONTENTS

ABSTRACT	I
ACKNOWLEDGEMENTS	II
NOMENCLATURE	VI
CHAPTER 1	
INTRODUCTION	1
1.1 History	1
1.2 Problem statement	4
1.3 Focus of this study	5
1.4 Aims of this study	5
1.5 Method of investigation	6
CHAPTER 2	
LITERATURE SURVEY	7
2.1 Effect of lubricant oil on the physical properties of oil-CO ₂ mixtures	7
2.2 Parameters influenced by the presence of lubricant oil	8
2.3 Convection heat transfer coefficient correlations	10
2.4 Influence of the dryout phenomenon on correlation accuracy	14
2.5 Summary	14
CHAPTER 3	
THEORETICAL CONSIDERATIONS AND CORRELATION EVALUATION	15
3.1 Theoretical background	15
3.1.1 Conservation laws	15
3.1.2 Mass flow rate	17

3.1.3	Heat transfer rate.....	18
3.1.4	Non-dimensional numbers.....	19
3.1.5	Dryout vapour quality prediction	21
3.1.6	Convection heat transfer coefficient correlation	21
3.1.7	Statistical concepts.....	22
3.2	Evaluation of correlation by Aiyoshizawa	24
3.2.1	Approach of evaluation	24
3.2.2	Results	25
3.3	Summary	27
 CHAPTER 4		
	CORRELATION DEVELOPMENT AND VERIFICATION.....	28
4.1	Post-dryout phenomenon	28
4.2	New correlation for predicting the dryout vapour quality.....	29
4.3	Convection heat transfer coefficient correlation development.....	31
4.4	Results summary - new heat transfer coefficient correlation	41
4.5	Summary	46
 CHAPTER 5		
	CONCLUSION	47
	BIBLIOGRAPHY	49
	APPENDIX A: CORRELATION EES CODES	51
	APPENDIX B: HTC DATA SETS	63
	APPENDIX C: DRYOUT VAPOUR QUALITY DATA SETS	80
	APPENDIX D: NEW FORMULA DEVELOPMENT DATA	82
	APPENDIX E: EQUATIONS OF NEW CORRELATION.....	85

APPENDIX F: EXPERIMENTAL SETUP / UNCERTAINTY ANALYSIS.....	87
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NOMENCLATURE

Symbol	Name	Units
A_{flow}	Face flow area	m^2
A_{wall}	Wall area	m^2
Bd	Bond number	<i>Dimensionless</i>
Bo	Boiling number	<i>Dimensionless</i>
c_p	Specific heat capacity at constant pressure	$kJ/kg \cdot K$
D	Diameter	m
D_b	Bubble diameter	m
D_H	Hydraulic diameter	m
D_{ref}	Reference diameter	m
F	Convective enhancement factor	<i>Dimensionless</i>
Fr	Froude number	<i>Dimensionless</i>
g	Gravitational acceleration constant	m/s^2
G	Mass flux	$kg/m^2 \cdot s$
G_{ref}	Reference mass flux	$kg/m^2 \cdot s$
h	Enthalpy	kJ/kg
h_{cb}	Two-phase heat transfer coefficient, convective boiling component	$kW/m^2 \cdot K$
h_{nb}	Two-phase heat transfer coefficient, nucleate boiling component	$kW/m^2 \cdot K$
h_e	Enthalpy at the outlet	kJ/kg

h_i	Enthalpy at the inlet	kJ/kg
h_{lg}	Enthalpy of vaporisation	kJ/kg
h_{tp}	Two-phase convection heat transfer coefficient	$\text{kW/m}^2 \cdot \text{K}$
HTC	Convection heat transfer coefficient	$\text{kW/m}^2 \cdot \text{K}$
HTC_{exp}	Experimental convection heat transfer coefficient	$\text{kW/m}^2 \cdot \text{K}$
HTC_{pred}	Predicted convection heat transfer coefficient	$\text{kW/m}^2 \cdot \text{K}$
k	Conduction heat transfer coefficient	$\text{kW/m} \cdot \text{K}$
k_l	Liquid phase conduction heat transfer coefficient	$\text{kW/m} \cdot \text{K}$
L	Length	m
M	Curve modification factor	<i>Dimensionless</i>
$\dot{m}$	Mass flow rate	kg/s
$\dot{m}_e$	Mass flow rate at outlet	kg/s
$\dot{m}_i$	Mass flow rate at inlet	kg/s
MAD	Mean absolute deviation	<i>Percentage</i>
MRD	Mean relative deviation	<i>Percentage</i>
N	Number of elements	<i>Dimensionless</i>
OCR	Oil concentration ratio	<i>Percentage</i>
p	Static pressure	kPa
p_0	Stagnation pressure	kPa
p_{0e}	Stagnation pressure at outlet	kPa

p_{0i}	Stagnation pressure at inlet	kPa
Pr	Prandtl number	<i>Dimensionless</i>
Pr_l	Liquid phase Prandtl number	<i>Dimensionless</i>
q	Heat flux	kW/m^2
$\dot{Q}$	Heat transfer rate	kW
$\dot{Q}_{inc}$	Incremental heat transfer rate	kW
$\dot{Q}_{total}$	Total heat transfer rate	kW
Re	Reynolds number	<i>Dimensionless</i>
Re_{avg}	Average two-phase Reynolds number	<i>Dimensionless</i>
Re_{tp}	Two-phase Reynolds number	<i>Dimensionless</i>
S	Boiling suppression factor	<i>Dimensionless</i>
S_{oil}	Oil contamination boiling suppression factor multiplier	<i>Dimensionless</i>
t	Time	s
T_b	Bulk fluid temperature	K
T_0	Stagnation temperature	K
T_{0e}	Stagnation temperature at outlet	K
T_{0i}	Stagnation temperature at inlet	K
V	Velocity	m/s
$\forall$	Volume	m^3
$\dot{W}$	Rate of work transfer	kW

x	Vapour quality	<i>Dimensionless</i>
X_{tt}	Lockhart-Martinelli parameter	<i>Dimensionless</i>
z	Elevation height	<i>m</i>
z_e	Elevation height at outlet	<i>m</i>
z_i	Elevation height at inlet	<i>m</i>

Greek Symbols

μ	Dynamic viscosity	<i>kg/m · s</i>
μ_l	Liquid dynamic viscosity	<i>kg/m · s</i>
μ_v	Vapour dynamic viscosity	<i>kg/m · s</i>
ν	Kinematic viscosity	<i>m²/s</i>
ρ	Density	<i>kg/m³</i>
ρ_l	Liquid density	<i>kg/m³</i>
ρ_v	Vapour density	<i>kg/m³</i>
σ	Surface tension	<i>kN/m</i>
Δp_{0L}	Stagnation pressure loss over the length	<i>kPa</i>

LIST OF TABLES

Table 1.1:	Comparison between ODP and GWP of some commonly occurring refrigerants (Padalkar & Kadam , 2010)	4
Table 2.1:	Experimental data sources from the study by Fang (Fang, et al., 2013)	11
Table 2.2:	Mean relative and absolute deviations for top five correlations evaluated by Fang (Fang, et al., 2013)	12
Table 2.3:	Experimental data sources from the study by Li (Li, et al., 2014).....	13
Table 2.4:	Mean absolute error and standard deviation for top five correlations evaluated by Li (Li, et al., 2014)	14
Table 3.1:	Results summary for correlation by Aiyoshizawa	27
Table 4.1:	Comparison between accuracies of dryout quality correlations	30
Table 4.2:	Results comparison: calculation condition (a).....	32
Table 4.3:	Results comparison: calculation condition (c).....	35
Table 4.4:	Results comparison: calculation conditions (b) and (d).....	36
Table 4.5:	Results comparison: calculation condition (c) - M factor incorporated	38
Table 4.6:	Results comparison: calculation condition (b) - M factor incorporated	39
Table 4.7:	Results comparison: calculation condition (d) - M factor incorporated	41
Table 4.8:	Results summary - Correlation by Aiyoshizawa vs. new correlation	43
Table 4.9:	Results summary for new correlation - uncertainty interval omitted	45
Table 4.10:	Results summary: complete data sets, Aiyoshizawa and new correlation	46

LIST OF FIGURES

Figure 1.1:	Rising trend of global average temperatures over time (Calm, 2008)	2
Figure 1.2:	Relative usage percentage of selected refrigerants from 1930 to 2000 (Padalkar & Kadam , 2010)	3
Figure 3.1:	Comparison plots for conditions (a) to (d) of results by Aiyoshizawa	26
Figure 4.1:	Experimental vs. predicted (Aiyoshizawa) convection HTC data: $q = 9$ [kW/m ²], $G = 360$ [kg/m ² s], $T_{sat} = 15$ [°C], $D = 2$ [mm], OCR = 5%	29
Figure 4.2:	Dryout quality vs. average Reynolds number	30
Figure 4.3:	Results comparison - new suppression factor, calculation condition (a)	32
Figure 4.4:	Effect of oil contamination on convection heat transfer coefficient.....	33
Figure 4.5:	Results comparison - incorporation of new oil contamination suppression factor, calculation condition (c)	34
Figure 4.6:	Results comparison - new suppression factors: plot (a) for calculation condition (b); and plot (b) for calculation condition (d)	35
Figure 4.7:	Results comparison - incorporation of curve modification factor, calculation condition (c).....	37
Figure 4.8:	Results comparison - incorporation of curve modification factor, calculation condition (b)	39
Figure 4.9:	Results comparison - incorporation of curve modification factor, calculation condition (d)	40
Figure 4.10:	Results comparison - calculation conditions (a) to (d) - new correlation	42
Figure 4.11:	Results comparison for new correlation - uncertainty interval omitted	44
Figure 4.12:	Convection heat transfer coefficient comparison plots for the results of the complete data set; (a) Aiyoshizawa et al. (2006), (b) New correlation, (c) New correlation with uncertainty interval omitted.....	45

CHAPTER 1

INTRODUCTION

1.1 History

Over the past few decades environmental concerns have become a significant motivating factor in the design and development of industrial and domestic products. The challenge lies therein to design for minimal impact on the environment, but simultaneously maintaining high efficiency levels and low production costs. This trend is also observed in the heating, ventilation, air conditioning and refrigeration (HVACR) industries where numerous fields have been identified for improvements to reduce the impact of refrigerants used in the industry on the environment (Gebreslassie, et al., 2009).

Two international treaties which influence the choice of refrigerants used in modern refrigeration cycle designs are the Montreal Protocol and the Kyoto Protocol. The Montreal Protocol is a protocol to the Vienna Convention for the Protection of the Ozone Layer. It was ratified on 16 September, 1987, enforced on January 1st, 1989, and has undergone eight revisions ever since. The Montreal Protocol was drawn up to protect the ozone layer by phasing out the production of substances responsible for ozone depletion (United Nations, 1987). The Kyoto Protocol extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC). Based on the premise that global warming exists due to unnatural quantities of CO₂ emissions, it obligates State Parties to commit to the cause of reducing greenhouse gas emissions. The Kyoto Protocol was agreed upon on 11 December, 1997, and came into being on 16 February, 2005. These protocols dictate that the total impact of refrigerants on global warming and ozone layer depletion throughout their lifecycles are to be determined and used as a factor in refrigerant selection during the design phase of refrigeration systems (United Nations, 1997).

Figure 1.1 depicts the rising trend of global ambient temperatures over time. This trend served as motivation for the Kyoto Protocol to justify the restrictions on the use of refrigerants which may potentially contribute to global warming. From the graph it is evident that the global average temperature has steadily increased since the start of the 20th century. This phenomenon is believed to have been caused primarily by the worldwide industrial revolution which started in the 18th century. By the mid-20th century the cumulative effect of the unregulated release of greenhouse gases into the atmosphere had already caused a notable increase in the average global temperature. The depletion of the ozone layer due to chemicals released by factories also contributed to the problem and steps were taken in an attempt to address the issue (Calm, 2008).

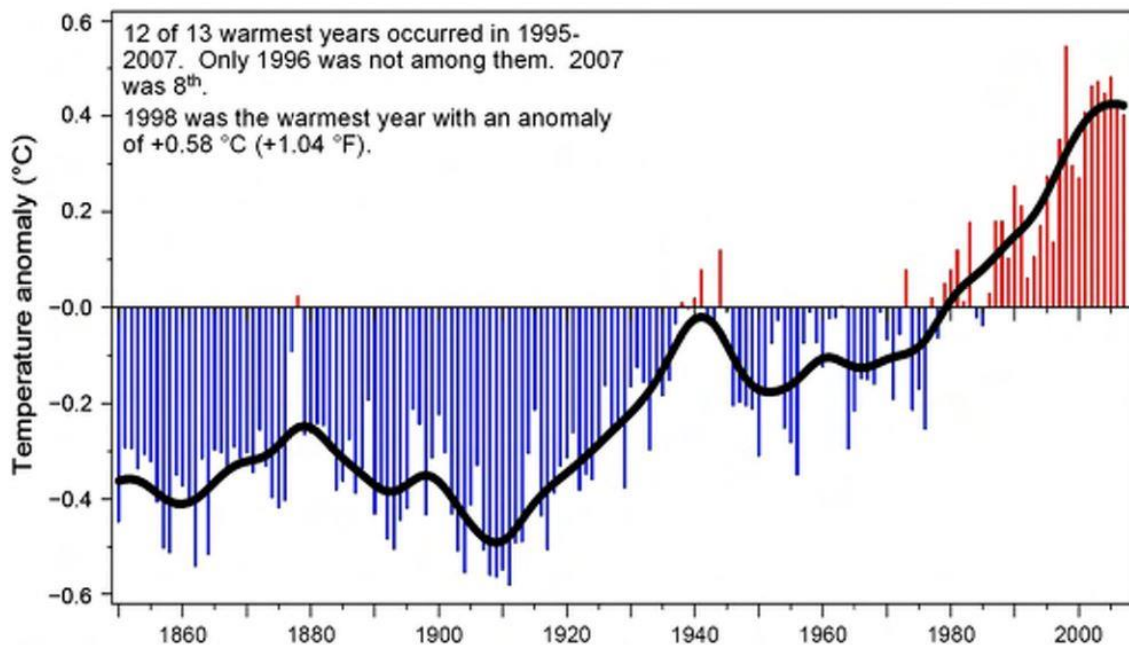


Figure 1.1: Rising trend of global average temperatures over time (Calm, 2008)

With all these factors as encouragement, it has been the goal of researchers to identify existing refrigerants or to develop new and improved refrigerants which have a minimal harmful impact on the environment, specifically the ozone layer. Two approaches to this are either to research naturally occurring gases or to identify other hydrofluorocarbons (HFC's) with less harmful environmental properties. The integrated aim of both approaches is to develop energy efficient refrigeration systems (Mohanraj, et al., 2009).

One naturally occurring gas deemed suitable for such an application is CO₂, also known by its refrigerant code, R-744. The use of CO₂ as a refrigerant can be traced back a few hundred years (Padalkar & Kadam , 2010). In early times of refrigeration equipment development, natural refrigerants such as CO₂, ammonia and sulphur dioxide were the most common types of refrigerants. In the late 1800's however, CO₂ was the preferred refrigerant for the majority of applications. The reason for this being that CO₂ is safer than ammonia and sulphur dioxide, since it is neither toxic nor flammable. Also, the use of ammonia and sulphur dioxide was legally restricted in some application areas (Nekså, 2004). Over time, research led to the development of synthetic chemical refrigerants such as chlorofluorocarbons (CFC's) - and HFC's. The development of these synthetic refrigerants resulted in natural refrigerants, specifically CO₂, being forced out by the 1940's. Refrigeration systems using synthetic refrigerants were safer and more economical in design, construction and operation (Nekså, 2004).

There exists multiple reason for the decline in use of CO₂ in the refrigeration industry and it is not possible to pinpoint one of these as the root cause. Some of the factors which might however have contributed to the decline in use thereof are the high working pressure of CO₂, as well as the loss of cooling capacity at high ambient temperatures due to the low critical point of CO₂. Also, synthetic refrigerants were widely marketed by the 1940's onward and by designing for these refrigerants the possibility of using low cost and lighter heat exchangers opened up. The inability to develop competitively priced components for CO₂ systems also contributed to the decline in the use of CO₂ as a refrigerant (Cavallini, 2010).

Figure 1.2 shows the general worldwide trend in the percentage of use relative to each other for some common refrigerants. It is evident that CO₂ was in prevalent use along with ammonia (NH₃) in the early 1900's. As time passed the use of synthetic chemical refrigerants such as R12 and R22 became more frequent and the use of the natural refrigerants declined. The R12 curve of Figure 1.2 has a negative slope from its peak in the 1960's onward to the present day. The curve for R22 reached a peak in the early 1990's, but it has since declined significantly because it is required by the Montreal Protocol that the use of R22 and some other ozone-depleting hydrochlorofluorocarbons (HCFC's) be completely stopped by the year 2021 (Pavkovic, 2013).

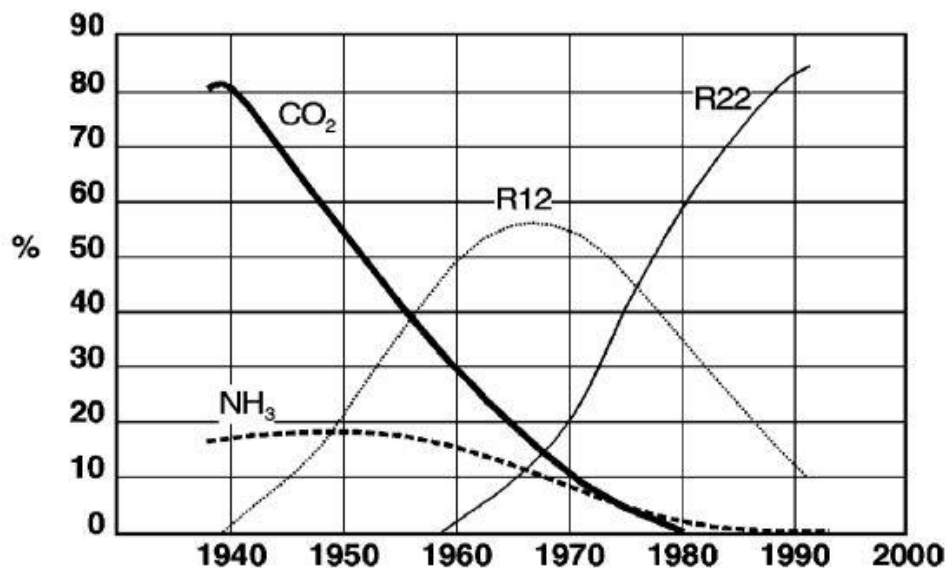


Figure 1.2: Relative usage percentage of selected refrigerants from 1930 to 2000 (Padalkar & Kadam , 2010)

As mentioned earlier, the focus was shifted back to natural refrigerants and specifically CO₂ in recent times because of its low global warming potential (GWP) and ODP. Due to the fact that the use of CO₂ as a refrigerant was phased out during the 1940's, significant research is desired to improve CO₂ refrigeration systems and to produce more cost efficient systems (Nekså, 2004).

Table 1.1 lists a few common refrigerants along with their ODP and GWP values. R22 and R134a are synthetic refrigerants both with a low ODP but a relatively high GWP. The natural refrigerants NH₃ and CO₂ have low ODP's and GWP's and would therefore be chosen over the synthetic refrigerants when the decision has to be made based solely on these environmental factors. Because of the toxicity of NH₃ and the health risks associated with it, CO₂ appears to be the better choice of natural refrigerant. The ODP and GWP along with toxicity to humans are not the only factors considered when selecting a refrigerant as they do not take into account system performance, but environmental considerations and requirements imposed by the Kyoto Protocol contribute to the weight of these factors (Bhatkar, et al., 2013).

Table 1.1: Comparison between ODP and GWP of some commonly occurring refrigerants (Padalkar & Kadam , 2010)

Refrigerant Code	R22	R134a	R717	R744
	CFC22	HFC134a	NH ₃	CO ₂
ODP / GWP	0.05 / 1700	0 / 1300	0 / 0	0 / 1

1.2 Problem statement

In order for CO₂ to replace conventional refrigerants there exists a number of design issues for which effective solutions must first be found. One of these issues is lubricant oil used in the compressor which inevitably leaks into and circulates through the system. The oil contamination affects the convection heat transfer in the evaporator and some previously conducted studies indicate that oil contaminated CO₂ refrigerant has a lower heat transfer coefficient than that of uncontaminated CO₂. It was also observed that the convection heat transfer coefficient gradually decreases with an increase in the oil concentration ratio (OCR) during the flow boiling process in the evaporator (Pehlivanoglu, et al., 2010).

In general, data showed that the convection heat transfer coefficient trend for oil contaminated and uncontaminated CO₂ responds in a similar manner to equivalent changes in system parameters, increasing as the heat flux, mass flux or saturation temperature is increased. The pressure drop due to friction at low temperatures for the oil contaminated CO₂ does not deviate significantly from that of uncontaminated CO₂. Various correlations for predicting the convection heat transfer coefficient of oil contaminated and uncontaminated CO₂ under flow boiling conditions exist, it is however necessary to investigate and evaluate the available correlations in order to determine their accuracy and usefulness (Pehlivanoglu, et al., 2010).

1.3 Focus of this study

Conventional convection heat transfer correlations are still used in most evaporator design calculations and are inadequate when applied to CO₂ due to the unique properties of the refrigerant (Li, et al., 2014). This study will investigate some existing CO₂ specific flow boiling convection heat transfer coefficient correlations for both oil contaminated and uncontaminated CO₂. Emphasis will be placed on those correlations which may be used in calculations for oil contaminated CO₂. The correlations investigated should take into account the effect of the OCR on convection heat transfer.

Experimental data obtained from previous studies by other researchers will be used to evaluate the most promising correlation identified from the investigation of this study. If it is found that the evaluated correlation is incapable of accurately predicting the convection heat transfer coefficient for oil contaminated and uncontaminated CO₂, this study will aim to develop a new correlation with improved prediction accuracy. The new correlation should also take into account the effect of the OCR on the convection heat transfer coefficient during evaporation. The OCR typically ranges from 0% to 5% for most refrigeration systems, and will therefore serve as the contamination limits investigated by this study (Dang, et al., 2013).

A previous study conducted by Strydom, focused on a thermal-fluid simulation of an air-to-CO₂ finned coil evaporator (Strydom, 2013). It was observed that the compressor lubricant that was present in the system had an influence on the heat transfer process and the flow regimes in the two-phase region of evaporation. It was also reported by Wang and Liaw (2012) that a lubricant foam formed at the interface of the liquid and gas phases at high heat fluxes and lubricant concentrations. This lubricant foam degraded the heat transfer coefficient when it was transported to the superheated region of the evaporator. It was attempted to use a degradation factor in the simulation model in order to compensate for this effect, but results indicated that the influence of the lubricant foam is complex and cannot be accurately modelled by applying a universal constant degradation factor (Wang & Liaw, 2012). A suggestion was made in the study by Strydom (2013) to further investigate the effects of lubricant oil contamination of CO₂ on the convection heat transfer coefficient in the evaporator section of a heat pump cycle (Strydom, 2013).

1.4 Aims of this study

This study will address the following aspects:

1. Investigate available flow boiling convection heat transfer coefficient correlations for CO₂, focusing on those correlations which take into account the effect of the OCR.
2. Select an existing correlation with high prediction accuracy from literature. Use experimental data with and without oil contamination to evaluate the selected correlation.

3. Investigate existing dryout vapour quality prediction correlations and if required develop a new correlation from experimental data.
4. If it is found to be necessary from the evaluation of the correlation in point 2, develop a new convection heat transfer coefficient correlation from experimental data for flow boiling conditions of CO₂ which does and does not take into account the effect of the OCR.

1.5 Method of investigation

Existing correlations for predicting the convection heat transfer coefficient of oil contaminated and uncontaminated CO₂ identified from literature will first be investigated. It will be required that the identified correlations should take into account the effect of the OCR on convection heat transfer. Evaluation of the correlations will be conducted in order to determine the accuracy of the correlations under specific calculation conditions. Experimental data from previous studies by other researchers will be used in the correlation evaluation process.

If it is found that none of the existing correlations are capable of accurately predicting the convection heat transfer coefficient for oil contaminated and uncontaminated CO₂ under flow boiling conditions, a new correlation will be developed from experimental data. The new correlation that will potentially have to be developed will also have to be evaluated by comparing its prediction results to the experimental data. It will be required that the new correlation should improve on the prediction accuracy of the existing correlations in order for the correlation development to be considered successful.

CHAPTER 2

LITERATURE SURVEY

The previous chapter served as introduction and presented the problem statement along with the focus and aims of this study and the method of investigation was also explained. This chapter will concentrate on the relevant available literature concerning the effect of lubricant oil on the thermodynamic properties of CO₂, the influence of lubricant oil on system parameters, the importance of the dryout phenomenon in the flow boiling convection heat transfer coefficient prediction of CO₂, as well as convection heat transfer coefficient correlations which may be applied to the flow boiling of CO₂ which take into account the effect of the OCR.

2.1 Effect of lubricant oil on the physical properties of oil-CO₂ mixtures

The thermodynamic properties of the oil contaminated CO₂ are different to those of uncontaminated CO₂. Some of the most important changes to the physical properties of oil contaminated CO₂ are briefly commented on below:

- **Density:** In most instances, the density of the lubricating oil will be lower than the density of the refrigerant in the liquid phase depending on the type of oil selected. The difference in density between the lubricant oil and CO₂ can be as much as 300 kg/m³. For polyalkylene glycol (PAG) type oil, which is the oil used in the study from where the experimental data for this study is obtained, the difference in densities is in the range of 100 kg/m³ (Bandarra Filho, et al., 2009) (Dang, et al., 2013).
- **Dynamic viscosity:** For two-phase flow conditions, the total convection heat transfer coefficient is proportional to the single phase liquid convection heat transfer coefficient in almost all existing correlations. The single phase liquid convection heat transfer coefficient is in some degree proportional to both the Reynolds and Prandtl numbers. From the definition of the Reynolds number (equation (3.18)) it follows that the viscosity of the fluid is inversely proportional towards this number and a change in the viscosity due to oil contamination will consequently affect the total convection heat transfer coefficient (Bandarra Filho, et al., 2009).
- **Surface tension:** The presence of lubricant oil in a refrigerant could potentially increase the surface tension of the mixture by as much as 18%. The most prominent effect that the greater surface tension has is that it increases the wetted perimeter of the tube through which the mixture flows. This results in an increased perimeter averaged heat transfer coefficient, but it is possible that it may also cause an increase in the pressure drop in the system (Bandarra Filho, et al., 2009).

- **Mass diffusion effect:** A refrigerant-oil mixture behaves like a wide boiling range mixture. The mixture has two components of which the oil is the higher boiling point component and the refrigerant the lower boiling point component. The higher boiling point component tends to accumulate at the interface of evaporation, which would be the inner wall of the evaporator tube, and the refrigerant is forced to diffuse through this oil rich layer slowing down the evaporation process. In addition to this additional resistance to heat transfer effect, the oil can create a surfactant effect and promote foaming. The effect of this on the heat transfer is not clear (Bandarra Filho, et al., 2009).
- **Immiscibility effect:** The miscibility of lubricant oil in a refrigerant is described as the capability of the oil to mix with the refrigerant used. Lubricant oil is either miscible or immiscible in a certain refrigerant and may sometimes depend on the temperature. Excellent miscibility of a lubricant oil in a certain refrigerant is desirable as this ensures that effective mixing of the oil and refrigerant occurs, enabling the oil to effectively pass throughout the system and back to the compressor. Immiscibility is not desirable since it causes the liquid phases of the oil and refrigerant to coexist and as a result droplets of oil form and cling to the wall of the tube. These droplets of oil will tend to greatly reduce the liquid film Reynolds number and subsequently decrease the heat transfer while increasing the pressure gradient (Bandarra Filho, et al., 2009). PAG oils are partially miscible in CO₂ and are used in a variety of CO₂ refrigeration applications (Zhao & Bansal, 2009).
- **Specific heat:** In most instances the specific heat of the lubricating oil in refrigeration systems is higher than the specific heat of the refrigerant in the liquid phase. For CO₂ systems with PAG oil however, this is not the case because the constant pressure specific heat for saturated liquid CO₂ at 0 °C is 2.43 kJ/kgK and that of the PAG oil at the same temperature is 2.05 kJ/kgK (Fernandez, 2008). The presence of PAG oil in CO₂ systems will therefore cause the refrigerant-oil mixture to have a lower specific heat than the pure refrigerant and subsequently reduce the heat transfer in the refrigeration system (Bandarra Filho, et al., 2009).
- **Thermal conductivity:** The thermal conductivity of the lubricant oil is generally higher than the thermal conductivity of the refrigerant in the liquid phase. This is also true for CO₂ and PAG lubricants and is considered a positive effect of oil contamination as it has the potential to improve the total heat transfer coefficient (Bandarra Filho, et al., 2009).

2.2 Parameters influenced by the presence of lubricant oil

In the convective boiling of refrigerants some parameters are influenced by the lubricant oil present in the system. These parameters include mass velocity, vapour quality, oil concentration

and the geometric characteristics of the tube (Bandarra Filho, et al., 2009). Below follows a discussion on how the presence of lubricant oil affects each of these parameters.

- **Mass velocity effect:** By varying the mass velocity of the refrigerant-oil mixture important observations have been made by various researchers. It is known that high mass velocities promote a more uniform refrigerant-oil mixture. This may lead to a reduction in the performance loss caused by the lubricant oil mainly because less oil clings to the tube wall resulting in improved heat transfer and therefore better performance. As observed with pure refrigerants, heat transfer increases with the mass velocity for refrigerant-oil mixtures. The degree of foaming in refrigerant-oil mixture flow undergoing convective boiling is also linked to the mass velocity. At low mass velocities where stratified or wavy flow is generally observed, the foaming formation occurs at the liquid-vapour interface. At higher mass velocities where annular flow patterns are observed, it is possible for froth flow to occur (Bandarra Filho, et al., 2009).
- **Vapour quality effect:** Because the lubricant oil is a nearly non-volatile component of the refrigerant-oil mixture, its partial pressure in the vapour phase is usually neglected. The vapour quality has a profound effect on the lubricant oil concentration. Since the lubricant oil remains in the liquid phase, its concentration increases with the vapour quality as the refrigerant evaporates. At higher nominal oil concentrations in the region of 5% or more, the local oil concentration can reach values of the order of 90% in the liquid component of the fluid mixture. This causes a significant increase in the viscosity of the refrigerant-oil mixture and the non-equilibrium effect becomes more significant (Bandarra Filho, et al., 2009).
- **Oil concentration effect:** It has been shown in various previous studies that the presence of lubricant oil in refrigeration systems above concentrations of 1% in mass reduces the convection heat transfer coefficient. This observed degradation in the heat transfer coefficient increases as the oil concentration is increased. Lubricant oil at high concentrations (above 5%) drastically reduces the flow boiling heat transfer coefficient. Under some conditions it has been observed that the presence of lubricant oil in concentrations around 3% may unexpectedly increase flow boiling heat transfer. The enhancement may depend on parameters such as the type of lubricant oil, the heat flux, the flow rate, flow patterns, the type of tube and possibly other unidentified factors; but the exact enhancement mechanism is unknown (Eckels, et al., 1994) (Schlager, et al., 1990a). It must be noted that the actual lubricant oil concentration in the heat exchanger of the refrigeration system depends on the particular setup of the system, i.e. if an oil separator is present, the miscibility of the lubricating oil and the type of system to name just a few (Bandarra Filho, et al., 2009).

- **Tube geometry effect:** As was previously mentioned, the mass velocity of the refrigerant-oil mixture can be increased to induce annular flow in the tubes in order to achieve improved heat transfer rates. In some instances the presence of lubricant oil may promote annular flow in smooth tubes. But when micro-fin tubes are used the annular flow pattern can be achieved at lower mass velocities and the presence of lubricant oil in the refrigerant can lose its benefit to induce annular flow (Bandarra Filho, et al., 2009).

2.3 Convection heat transfer coefficient correlations

Comparative reviews of existing correlations for flow boiling heat transfer coefficient of CO₂ were conducted by both Fang et al. (2013) and Li et al. (2014). The investigation by Fang et al. (2013) included only correlations for uncontaminated CO₂, therefore neglecting the influence of lubricating oil on the convection heat transfer coefficient, and was very comprehensive, analysing and evaluating 34 correlations with 2956 experimental data points of CO₂ flow boiling convection heat transfer from 10 independent laboratories (Fang, et al., 2013). The investigation conducted by Li et al. (2014) examined six correlations for the flow boiling convection heat transfer coefficient of CO₂ and considered the effect of lubricant oil contamination on convective heat transfer. Evaluation in the study by Li et al. (2014) was performed by comparing the predicted correlation results to 521 experimental data points obtained from six previous studies by various other researchers. The study by Li et al. (2014) did however only consider experimental data points located in the pre-dryout region (up to a vapour quality of around 0.7), subsequently limiting the scope of the evaluation since no remarks can be made regarding the post-dryout prediction accuracies of the correlations (Li, et al., 2014).

The experimental data sources used in the comparative review by Fang et al. (2013) are listed in Table 2.1. These data sources are all for flow boiling of uncontaminated CO₂. The parameter range, geometry range and number of data points of each data source are listed.

Table 2.1: Experimental data sources from the study by Fang (Fang, et al., 2013)

Data source	Parameter range: $T_{sat}(^{\circ}\text{C})/p_{sat}(\text{MPa})/G$ ($\text{kg}/\text{m}^2\text{s})/q(\text{kW m}^{-2})/x$	Geometry range: $D_h(\text{mm})/L(\text{mm})/$ Tube material	Number of data points
Cho and Kim (2007)	0–20/3.5–5.7/212–656/6–20/0.05–0.94	①4/5000; ②7.72/5000/ ^a	180
Yun et al. (2003)	5–10/3.97–4.5/170–340/10–20/0.09–0.92	6/1400/Stainless steel	82
Zhao and Bansal (2007)	–29.9– –28.6/1.43–1.5/139.5–230.9/12.6–19.3/0.13–0.94	4.57/4500/Stainless steel	22
Wu et al. (2011)	–40–0/1.0–3.49/300–600/7.5–29.8/0.02–0.998	1.42/300/Stainless steel	372
Oh and Son (2011)	5–20/3.97–5.7/400–900/20–40/0.01–0.9	①4.57/4200; ②7.75/4200/Stainless steel	112
Mastrullo et al. (2009, 2010)	–7.8–5.8/2.8–4.05/200–349/9.6–20.3/0.02–0.98	6/1200/Stainless steel	164
Oh et al. (2008)	–5–5/3.05–3.97/200–500/10–30/0.007–0.77	7.75/5000/Stainless steel	80
Oh et al. (2011)	1–10/3.58–4.5/300/20–30/0.04–0.93	3/2000/Stainless steel	47
Park and Hrnjak (2007)	–30 to –15/1.43–2.29/97.5–408.6/5–15.5/0.08–0.83	①6.1/150; ②3.5/150/Brass	210
Ducoulombier et al. (2011)	–10–0/2.64–3.49/200–1400/10–30/0–0.99	0.529/159.3/Stainless steel	1270
Pamitran et al. (2011)	1–10/3.57–4.5/200–600/20–30/0.01–0.99	①1.5/2000; ②3/2000/Stainless steel	162
Ozawa et al. (2009)	21.98–26.76/6–6.7/300/10–25/0.02–0.88	2/1850/Stainless steel	74
Ma (2005)	5.3–6.3/4–4.1/200–400/3.93–24.42/0.05–0.78	1.127/897/Stainless steel	181

^a Material was not mentioned in the paper.

Nine of the thirty-four correlations investigated by Fang et al. (2013) are CO₂-specific correlations for flow boiling heat transfer coefficients. These nine CO₂-specific correlations are:

- Tenaka et al. (2001)
- Wang et al. (2003)
- Yoon et al. (2004a,2004b)
- Thome and El Hajal (2004)
- Choi et al. (2007)
- Cheng et al. (2008a,2008b)
- Ducoulombier et al. (2011)
- Pamitran et al. (2011)
- Fang (2013)

Of the thirty-four correlations evaluated against the data sources listed in Table 2.1, the five most accurate, in order of most to least accurate, are:

- Fang (2013)
- Gungor and Winterton (1987)
- Jung et al. (1989)
- Cheng et al. (2008a,2008b,2012)
- Saitoh et al. (2007)

Table 2.2 shows the mean relative deviation (MRD) and the mean absolute deviation (MAD) for these five correlations when evaluated against each of the data sets of Table 2.1.

Table 2.2: Mean relative and absolute deviations for top five correlations evaluated by Fang (Fang, et al., 2013)

Data source	Deviation, %	Correlation				
		Fang (2013)	Gungor and Winterton (1987)	Jung et al. (1989)	Cheng et al. ^a	Saitoh et al. (2007)
Cho and Kim (2007)	MRD	−3.1	−25.9	−0.4	12.0	−26.7
	MAD	19.1	33.5	37.8	39.4	42.6
Yun et al. (2003)	MRD	−7.9	−36.7	−18.2	21.8	−34.7
	MAD	11.7	37.8	24.2	35.3	40.5
Zhao and Bansal (2007)	MRD	4.0	−7.1	14.1	38.4	8.6
	MAD	7.9	9.6	20.2	44.8	15.8
Wu et al. (2011)	MRD	−6.1	−13.8	17.2	−8.1	18.8
	MAD	16.0	46.1	54.5	29.7	57.1
Oh and Son (2011)	MRD	−10.1	−19.6	11.5	18.3	−37.7
	MAD	15.8	33.8	36.2	30.5	50.5
Mastrullo et al. (2009, 2010)	MRD	−2.3	−27.4	−9.7	22.6	−24.0
	MAD	9.0	27.9	20.8	38.2	27.0
Oh et al. (2008)	MRD	5.7	−15.0	4.4	62.1	−27.0
	MAD	11.5	27.2	23.4	63.8	35.4
Oh et al. (2011)	MRD	5.6	−11.5	22.3	63.4	8.3
	MAD	24.4	15.1	30.1	68.8	10.4
Park and Hrnjak (2007)	MRD	4.8	−31.3	−15.2	8.6	−26.7
	MAD	19.7	33.8	30.5	20.2	29.4
Ducoulombier et al. (2011)	MRD	−0.5	−16.5	5.6	−7.3	0.4
	MAD	13.8	33.2	31.1	28.9	33.2
Pamitran et al. (2011)	MRD	6.6	3.4	36.4	66.9	10.9
	MAD	19.9	16.5	40.0	71.7	12.3
Ozawa et al. (2009)	MRD	−5.5	−38.1	9.4	19.1	−4.4
	MAD	23.1	41.1	29.9	26.1	39.9
Ma (2005)	MRD	5.8	−13.9	−7.9	30.4	11.9
	MAD	16.6	17.9	18.4	36.7	23.7
Total data	MRD	−0.3	−18.8	5.2	9.1	−4.0
	MAD	15.5	32.5	33.2	34.2	35.0

The experimental data sources used in the review by Li et al. (2014) are listed in Table 2.3. The tube geometry, heat flux, mass flux, oil concentration ranges, oil test methods, saturation temperature and number of data points are listed in the table for each of the data sources.

Table 2.3: Experimental data sources from the study by Li (Li, et al., 2014)

References	Tube inner	Heat flux	Mass flux	Oil concentration
	D (mm), L (m)	(kW m^{-2})	$(\text{kg m}^{-2} \text{s}^{-1})$	(%)
Katsuta et al. (2008a)	Smooth stainless $D = 3$ mm, $L = 0.5$ m	5, 10, 15 Electric heating	400	PAG 100, 0%, 0.05%–0.5%, 0.6%–1.2%, 1.8%–2.5%, 3.0%–4.0%
Katsuta et al. (2008b)	Smooth stainless $D = 3$ mm, $L = 0.5$ m	10 Electric heating	200, 400, 600	PAG 0%–0.05%, 0.5%–1.0%, 1.0%–2.0%, 2.0%–3.0%, 3.0%–5.0%, 7.0%–9.0%
Gao et al. (2008)	Smooth stainless inner $D = 3.76$ mm	10, 20, 30 Electric heating	100, 190, 380	PAG 1.01% PAG < 0.01%, 0.09%, 0.17%, 0.48%, 0.72%
Gao et al. (2007)	Smooth stainless $D = 3$ mm, $L = 2.185$ m; Micro-fin $D = 3.04$ mm, Fin height = 0.11 mm	5, 10, 20, 30 Electric heating	190, 380, 770, 390, 780, 1180	PAG 0.01%, 0.11%, 0.30%, 0.57%
Zhao et al. (2002)	Mini tube $D = 0.86$ mm	11	300	Oil type N/A 0%, 1%, 3%, 4%, 5%, 7%
Dang et al. (2013)	Smooth stainless $D = 2$ mm	4.5, 9, 18, 36 Electric heating	360, 720, 1440	PAG 100, 0%, 1%, 3%, 5%
References	Oil test methods	Saturated temperature $(^{\circ}\text{C})$	Number of data items $\omega_o > 0.05\%$	
Katsuta et al. (2008a)	Oil supply system, oil mass flow meter, and oil sampling tank	–10, 0, 10	55	
Katsuta et al. (2008b)		0	34	
Gao et al. (2008)	Measured from the size and time interval of an oil droplet falling into the sight glass chamber	10	51	
Gao et al. (2007)		10	53	
Zhao et al. (2002)	N/A	10	54	
Dang et al. (2013)	Oil sampling tube	15	274	

When evaluated against the data in Table 2.3, the five most accurate correlations in the study by Li et al. (2014) from most to least accurate are:

- Aiyoshizawa et al. (2006)
- Gao et al. (2008)
- Katsuta et al. (2008a)
- Hwang et al. (1997)
- Thome and El Hajal (2004)

The data from the study by Dang et al. (2013) will be used in this study because it contains the greatest number of data items. The boundaries for the data by Dang et al. (2013) are given in Table 2.3.

Table 2.4: Mean absolute error and standard deviation for top five correlations evaluated by Li (Li, et al., 2014)

	Katsuta et al. (2008a, 2008b)		Zhao et al. (2002)		Dang et al. (2013)		Gao et al. (2007, 2008)	
	Mean absolute error	Standard deviation	Mean absolute error	Standard deviation	Mean absolute error	Standard deviation	Mean absolute error	Standard deviation
Thome and El Hajal (2004)	–146%	290%	–141%	255%	194%	400%	196%	399%
Hwang et al. (1997)	63%	136%	32%	57%	123%	243%	109%	234%
Katsuta et al. (2008a)	42%	25%	46%	24%	21%	39%	21%	11%
Gao et al. (2008)	53%	112%	61%	118%	62%	129%	64%	141%
Aiyoshizawa et al. (2006)	32%	21%	40%	22%	10%	9%	14%	11%

Table 2.4 shows that the study by Li et al. (2014) identified the correlation by Aiyoshizawa et al. (2006) as the most accurate correlation which also takes into consideration the effect of oil contamination on the flow boiling convection heat transfer. A point of concern for the study conducted by Li et al. (2014) is that only the pre-dryout region of the two-phase flow boiling process was considered in evaluating the correlations (Li, et al., 2014).

2.4 Influence of the dryout phenomenon on correlation accuracy

In the study by Fang et al. (2013) it is stressed that the dryout inception criterion of CO₂ flow boiling heat transfer is an important issue and a big challenge. The study revealed that it is only after the inception of dryout that most correlations fail to predict the heat transfer coefficient accurately. Dryout has a great effect on CO₂ flow boiling heat transfer and dryout concerns are more serious for mini/microchannels than for conventional channels. Fang et al. (2013) evaluated four correlations containing the criterion for dryout inception, which include the correlations of Cheng et al. (2008a, 2008b, 2012), Thome and El Hajal (2004), Yoon et al. (2004a, 2004b) and Saitoh et al. (2007). But it was found that none of these four correlations could predict the dryout phenomenon satisfactorily. The reason for this was noted that the observation of dryout inception is extremely difficult. For the development of an accurate heat transfer correlation for CO₂, great effort should be made towards understanding the dryout phenomenon and work must be done on predicting the dryout vapour quality inception point (Fang, et al., 2013).

2.5 Summary

It was determined that oil contamination of CO₂ has a definite degradation effect on the flow boiling convection heat transfer coefficient. Observations regarding some system parameters and how they may possibly be influenced by oil contamination were discussed. Correlations for predicting the convection heat transfer coefficient of flow boiling CO₂ were considered and the influence of the dryout phenomenon on correlation accuracy was also briefly discussed. The next chapter will provide theoretical background for this study and the correlation by Aiyoshizawa et al. (2006) will be evaluated using the data obtained from the study of Dang et al. (2013).

CHAPTER 3

THEORETICAL CONSIDERATIONS AND CORRELATION EVALUATION

The previous chapter focussed on available literature relevant to this study. The influence of oil contamination on mixture properties and system parameters was explained and some existing convection heat transfer coefficient correlations for flow boiling CO₂ were considered. The influence of the dryout phenomenon on correlation accuracy was also briefly discussed.

The first part of this chapter will focus on the theoretical background for this study. Applicable conservation laws will be presented and explained in the context of this study. Heat and mass transfer rate equations will also be given and discussed. Various non-dimensional numbers used in this study will be defined and their equations provided. A correlation for calculating the dryout vapour quality as obtained from the study by Katsuta et al. (2008) will be presented. A correlation by Aiyoshizawa et al. (2006) for predicting the convection heat transfer coefficient in the flow boiling of CO₂ will also be given. Some statistical entities used in this study are also defined.

The second part of this chapter evaluates the correlation by Aiyoshizawa et al. (2006) using the experimental data obtained from the study by Dang et al. (2013). The calculation results are presented for the different calculation conditions and a direct comparison is made between the experimental and predicted values of the flow boiling convection heat transfer coefficients in order to identify any shortcomings of the correlation by Aiyoshizawa et al. (2006). The results are discussed and observations are made regarding the adequacy of the correlation by Aiyoshizawa.

3.1 Theoretical background

3.1.1 Conservation laws¹

The conservation laws which form an integral part of thermodynamic studies include the conservation of mass, momentum and energy. Each of these conservation laws describe a quantity that is conserved, that is, the total amount is the same before and after the occurrence of an event. For each of these laws it is important to know whether the calculations in which they are applied are steady-state or transient as well as if the flow is compressible or incompressible, as these factors influence the formulation of the conservation laws. For this study it has been assumed that steady-state flow conditions apply, no pressure losses occur, flow takes place horizontally with no changes in elevation and the total temperature in the two-phase flow region remains constant at the same total pressure.

¹ The discussions in Sections 3.1.1 to 3.1.3 are based on the work of (Rousseau, 2014).

Conservation of mass

For the conservation of mass, the following generic equation is presented:

$$\forall \frac{\partial \rho}{\partial t} + \dot{m}_e - \dot{m}_i = 0 \quad (3.1)$$

where $\forall \left[m^3 \right]$ is the volume of the fluid, $\rho \left[kg/m^3 \right]$ the density, $t \left[s \right]$ the time and $\dot{m} \left[kg/s \right]$ the mass flow rate.²

But for the simplifying assumptions of this study, it follows that:

$$\dot{m}_e - \dot{m}_i = 0 \quad (3.2)$$

Which shows that the out- and inlet mass flow rates are equal and, therefore, only a single symbol, $\dot{m}$, may be used to represent the mass flow rate, thereby simplifying the equation to:

$$\dot{m} = \dot{m}_i = \dot{m}_e \quad (3.3)$$

Conservation of momentum

The generic equation presented for incompressible flow is as follows:

$$\rho L \frac{\partial V}{\partial t} + (p_{0e} - p_{0i}) + \rho g (z_e - z_i) + \Delta p_{0L} = 0 \quad (3.4)$$

where $L \left[m \right]$ is the incremental length, $V \left[m/s \right]$ is the velocity, $p_0 \left[kPa \right]$ the total pressure, $g \left[m/s^2 \right]$ the constant gravitational acceleration, $z \left[m \right]$ the elevation height and $\Delta p_{0L} \left[kPa \right]$ the pressure loss over the incremental length.

For the simplifying assumptions of this study it follows that:

$$p_{0e} - p_{0i} = 0 \quad (3.5)$$

The generic equation presented for compressible flow is as follows:

$$\rho L \frac{\partial V}{\partial t} + \frac{p}{p_0} (p_{0e} - p_{0i}) + \frac{1}{2} \rho V^2 \frac{1}{T_0} (T_{0e} - T_{0i}) + \rho g (z_e - z_i) + \Delta p_{0L} = 0 \quad (3.6)$$

where $p \left[kPa \right]$ is the static component of the total pressure and $T_0 \left[K \right]$ is the total temperature.

² In this study the subscripts e and i always denote outlet and inlet conditions respectively.

For the simplifying assumptions made for this study and after some manipulation of the formula it follows that:

$$p_{0e} - p_{0i} = 0 \quad (3.7)$$

which is the same expression obtained for the conservation of momentum for incompressible flow as is indicated by equation (3.5). It is therefore unnecessary to differentiate between compressible and incompressible flow for this study with its simplifying assumptions.

A single symbol, p_0 , may be used to represent the pressure:

$$p_0 = p_{0i} = p_{0e} \quad (3.8)$$

Conservation of energy

For the conservation of energy, the following generic equation is presented:

$$\dot{Q} + \dot{W} = V \frac{\partial(\rho h - p)}{\partial t} + \dot{m}_e h_e - \dot{m}_i h_i + \dot{m}_e g z_e - \dot{m}_i g z_i \quad (3.9)$$

where $\dot{Q}$ [kW] is the total rate of heat transfer to the fluid, $\dot{W}$ [kW] is the total rate of work done on the fluid and h [kJ/kg] the enthalpy.

For the heat transfer calculations of this study no work is done on the fluid, therefore $\dot{W} = 0$. By the substitution of equation (3.3) and applying the simplifying assumptions of this study, it follows that:

$$\dot{Q} = \dot{m}(h_e - h_i) \quad (3.10)$$

3.1.2 Mass flow rate

From the overview of the conservation laws, it follows that the mass flow rate is required for energy conservation calculations. The mass flow rate is defined as:

$$\dot{m} = \rho V A_{flow} \quad (3.11)$$

where A_{flow} [m²] is the area of the tube perpendicular to the flow.

In some instances, the mass flux is specified rather than the mass flow rate. The mass flux G [kg/m² · s] is defined by:

$$G = \rho V \quad (3.12)$$

The expression for the mass flow rate can therefore also be written as:

$$\dot{m} = GA_{flow} \quad (3.13)$$

For a simple circular tube with constant mass flux the perpendicular flow area of the tube can be calculated using the following formula:

$$A_{flow} = \frac{1}{4} \pi D^2 \quad (3.14)$$

where D [m] represents the inner diameter of the tube.

3.1.3 Heat transfer rate

In the calculations of this study, constant heat flux is assumed and a number of equations are used to calculate the heat transfer rate between the tube wall and the fluid flowing in the tube.

Total heat transfer rate

For a fixed length tube with constant heat flux, the total heat transfer rate from the tube wall to the fluid can be calculated using:

$$\dot{Q}_{total} = qA_{wall} \quad (3.15)$$

where q [kW/m²] is the constant heat flux and A_{wall} [m²] is the total surface area of the inner wall of the tube and can be calculated by:

$$A_{wall} = \pi DL \quad (3.16)$$

where L [m] is the total length of the tube.

Incremental heat transfer rate

The incremental heat transfer rate can be calculated using:

$$\dot{Q}_{inc} = \dot{Q}_{total} / N \quad (3.17)$$

where N is the total number of vapour quality increments used in the calculations.

3.1.4 Non-dimensional numbers³

In order to calculate the convection heat transfer coefficient it is necessary to first calculate certain non-dimensional numbers. These include the Re , Pr , Bo , Bd and Fr numbers, each of which are explained in the following section.

The Reynolds number

The non-dimensional Reynolds (Re) number is a quantity that may be interpreted as the ratio of the inertial forces to the viscous forces in the velocity boundary layer of the fluid. The Re number is defined as:

$$Re = \frac{\rho VL}{\mu} \quad (3.18)$$

where μ [$kg/m \cdot s$] is the fluid dynamic viscosity.

When considering flow in a tube, the Re number may be calculated as follows:

$$Re = \frac{\rho V D_H}{\mu} \quad (3.19)$$

where D_H [m] is the hydraulic diameter of the tube. For circular tubes with fully wetted perimeter flow however, the hydraulic diameter is equal to the tube diameter:

$$D_H = D \quad (3.20)$$

The Prandtl number

The non-dimensional Prandtl (Pr) number is a quantity that may be interpreted as the ratio of the ability to transport momentum versus the ability to transport energy through diffusion in both the velocity and thermal boundary layers of the fluid flow. The Pr number is defined as:

$$Pr = \frac{c_p \mu}{k} \quad (3.21)$$

where c_p [$kJ/kg \cdot K$] is the specific heat capacity at constant pressure and k [$kW/m \cdot K$] is the thermal conductivity of the fluid under consideration.

³ The discussions in Section 3.1.4 are based on the work by (Li, et al., 2014).

The Boiling number

The non-dimensional Boiling (Bo) number is a quantity that represents the stirring effect of the bubbles upon the flow in two-phase flow heat transfer calculations. The Bo number can be thought of as a ratio of mass flow rates per unit area and is defined as:

$$Bo = \frac{q}{Gh_{lg}} \quad (3.22)$$

where h_{lg} [kJ/kg] is the enthalpy of vaporization.

The Bond number

The non-dimensional Bond (Bd) number arises from the analysis of the behaviour of bubbles and drops. It represents the ratio of the gravitational force to the surface tension force. The Bd number is defined as:

$$Bd = \frac{g\rho D^2}{\sigma} \quad (3.23)$$

where σ [kN/m] is the surface tension of the fluid.

The Froude number

The non-dimensional Froude (Fr) number measures the ratio of the inertial force on an element of fluid to the weight of the fluid element, or the inertial force divided by the gravitational force. The Fr number is defined as:

$$Fr = \frac{v^2}{gD} \quad (3.24)$$

where ν [m^2/s] is the fluid kinematic viscosity.

3.1.5 Dryout vapour quality prediction⁴

To predict the onset quality of dryout, the study by Katsuta et al. (2008), hereafter referred to only as Katsuta, proposed the following correlation:

$$x_{dryout} = 0.269 \times \frac{Re^{0.0571} Fr^{0.0697}}{Bo^{0.0519}} \times \eta \quad (3.25)$$

Premature dryout factor η with oil contamination is determined using the oil concentration ratio (OCR) as follows:

$$\eta = 1 \text{ for } OCR < 1 \quad (3.26)$$

$$\eta = 1.169e^{-0.17 \times OCR} \text{ for } OCR \geq 1 \quad (3.27)$$

3.1.6 Convection heat transfer coefficient correlation⁵

The two-phase heat transfer coefficient proposed by Aiyoshizawa et al. (2006), hereafter referred to as only Aiyoshizawa, is expressed as:

$$h_{tp} = Fh_{cb} + Sh_{nb} \quad (3.28)$$

where h_{tp} [$kW/m^2 \cdot K$] is the total two-phase convection heat transfer coefficient, h_{cb} [$kW/m^2 \cdot K$] is the convective boiling component and h_{nb} [$kW/m^2 \cdot K$] is the nucleate boiling component. The factors F and S are the convective enhancement factor and boiling suppression factor respectively.

The expressions for each of these terms are as follows:

$$h_{cb} = 0.023 \frac{k_l}{D} \left[\frac{G(1-x)D}{\mu_l} \right]^{0.8} Pr^{0.4} \quad (3.29)$$

$$h_{nb} = 207 \frac{k_l}{D_b} \left(\frac{qD_b}{k_l T_b} \right)^{0.745} \left(\frac{\rho_v}{\rho_l} \right)^{0.581} Pr_l^{0.533} \quad (3.30)$$

$$F = 0.8 + 0.5 \left(\frac{1}{X_{tt}} \right)^{1.2} \quad (3.31)$$

⁴ The discussions in section 3.1.5 are based on the work by (Katsuta, et al., 2008).

⁵ The discussions in Section 3.1.6 are based on the work by (Aiyoshizawa, et al., 2006).

$$S = \frac{1}{6 + (Re_{tp} \times 10^{-4})^3} \quad (3.32)$$

where x is the vapour quality, D_b [m] is the bubble diameter, X_{tt} is the Lockhart-Martinelli parameter and Re_{tp} is the two-phase Reynolds number. Expressions for D_b , X_{tt} and Re_{tp} are:

$$D_b = 0.51 \left[\frac{2\sigma}{g(\rho_l - \rho_v)} \right]^{0.5} \quad (3.33)$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.1} \quad (3.34)$$

$$Re_{tp} = \left[\frac{G(1-x)D}{\mu_l} \right] F^{1.25} \quad (3.35)$$

3.1.7 Statistical concepts⁶

The statistical entities used in this study are the:

- mean
- standard deviation
- mean absolute deviation
- mean relative deviation

The mean and standard deviation are probably the most well-known and simple of the statistical entities. Below follows an explanation of each of the entities listed.

Mean

The mean or average, $\bar{y}$, is the summation of numerical values divided by the number of summation parameters, N , and is defined by the following formula:

$$\bar{y} = \frac{1}{N} \sum_{i=1}^N y_i \quad (3.36)$$

where y_i may represent any one of the numerical parameters.

⁶ The discussions in Section 3.1.7 are based on the work of (Fang, et al., 2013).

Standard deviation

The population standard deviation is defined as:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \bar{y})^2} \quad (3.37)$$

where $\bar{y}$ refers to the population mean and N to the number of data points in the sample. y_i refers to each of the sample data points from the population.

The sample standard deviation is defined as:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (y_i - \bar{y})^2} \quad (3.38)$$

where $\bar{y}$ refers to the sample mean and N to the number of data points in the sample.

Mean absolute deviation

The mean absolute deviation is a statistical parameter used to measure prediction accuracy. The mean absolute deviation is defined as:

$$MAD = \frac{1}{N} \sum_{i=1}^N \left| \frac{y(i)_{pred} - y(i)_{exp}}{y(i)_{exp}} \right| \quad (3.39)$$

where the subscripts *pred* and *exp* refer to the corresponding predicted and experimental data points respectively.

Mean relative deviation

The mean relative deviation is a statistical parameter used to investigate whether a correlation over- or under-predicts the sample size relative to the experimental average. The mean relative deviation is defined as:

$$MRD = \frac{1}{N} \sum_{i=1}^N \frac{y(i)_{pred} - y(i)_{exp}}{y(i)_{exp}} \quad (3.40)$$

3.2 Evaluation of correlation by Aiyoshizawa

This section will explain the approach followed in evaluating the correlation by Aiyoshizawa. Some of the previously supplied theory is used here. Calculations were conducted in EES to test the correlation by Aiyoshizawa against the experimental data of Dang et al. (2013), hereafter referred to only as Dang. The calculation results for all the calculation conditions will be given and observations regarding the accuracy of the correlation by Aiyoshizawa will be made following comparison with the experimental data. It is however important to note here that the uncertainties of the main measurement devices used in the study by Dang were not taken into consideration in the calculations of this study. The experimental results provided by the study of Dang were used as given. According to uncertainty analysis performed by Dang, the maximum measurement uncertainty of the heat transfer coefficient was between 8.9% and 13% (Dang, et al., 2013).⁷

3.2.1 Approach of evaluation

The experimental setup used in the calculations of this study is identical to the experimental setup used in the study by Dang and consists of a horizontal smooth tube of fixed length and diameter.⁸ There are no changes in elevation throughout, with a single inlet and single outlet. The tube material is not specified for this study as conduction heat transfer through the wall of the tube is not considered, only convection heat transfer from the wall to the CO₂ flowing through the tube. In order to simplify calculations, it is assumed that there are no pressure losses in the system and steady-state conditions prevail. It is also assumed that the fluid is in the saturated liquid state at the inlet of the tube and in the saturated vapour state at the outlet of the tube in order to obtain calculation results for the entire two-phase vapour quality range of the flow boiling process. Input parameter values used in the calculations were obtained directly from the experimental data sets of Dang to allow direct comparison of calculation results to the experimental data.

Using the experimental setup and the input parameters obtained from the experimental data of Dang, the EES code contained in Appendix A first calculates the properties of the CO₂ at the in- and outlet of the tube. Also the tube geometry is calculated using equations (3.14) and (3.16). The total heat transfer rate to the fluid between the in- and outlet of the tube can then be calculated using the given heat flux and equation (3.15) from which the incremental heat transfer rate is calculated using equation (3.17). The constant mass flow rate is calculated from the given mass flux and equation (3.13). A duplicate is initiated which uses the incremental heat transfer rate to find the in- and outlet enthalpy values for each of the increments using equation (3.10) and the calculated constant mass flow rate. The average two-phase properties are then determined using

⁷ See Table F.2 of Appendix F for the measuring device uncertainty of the study by Dang et al. (2013).

⁸ Refer to Appendix F for the experimental setup of Dang et al. (2013) used in this study.

the built-in EES functions. Once all the properties of the CO₂ have been calculated for each of the equal vapour quality increments, they are sent to a procedure which uses the correlation by Aiyoshizawa to calculate the average convection heat transfer coefficient for each increment using equations (3.28) to (3.35). Equations (3.25) to (3.27) by Katsuta are used in a separate function to calculate the predicted dryout vapour quality for the given set of input parameters. Refer to Appendix A for the relevant EES code used to perform the calculations of this study. Appendix A also contains an explanation of the calculation procedure, should the calculations need to be performed using a software package other than EES.

The calculated results are plotted against the experimental values by Dang for the same set of input parameters and Figure 3.1 shows comparison plots for all 1975 data points making up the 28 data sets. Interpolation methods are used to find the calculated convection heat transfer coefficient corresponding to the exact vapour quality at which the experimental values by Dang were obtained. The results are also stored in an array table from which the data can be extracted.

3.2.2 Results

Convection heat transfer coefficients calculated for different input parameters using the correlation by Aiyoshizawa will be compared to the experimental convection heat transfer coefficients as was obtained from the study by Dang.⁹

A total of 28 data sets each with different input parameters were considered in this study. In order to simplify the process of identifying shortcomings and detecting inaccuracies, four different comparison plots for the two-phase flow convection heat transfer coefficient are used. The four convection heat transfer coefficient comparison plots for their specific calculation conditions are as follows:

- (a) CO₂ with no oil contamination, for pre-dryout;
- (b) CO₂ with no oil contamination, for post-dryout;
- (c) CO₂ with oil contamination, for pre-dryout;
- (d) CO₂ with oil contamination, for post-dryout.

The four comparison plots of Figure 3.1 are used to analyze the accuracy of the Aiyoshizawa correlation. The two red diagonal lines on the plots of Figure 3.1 on either side of the ($y = x$) orange diagonal line indicate a 20% deviation, either a 20% over-prediction or a 20% under-prediction. The predicted convection heat transfer coefficient which was calculated is plotted on the y-axis while the experimental convection heat transfer coefficient obtained from the work by Dang is plotted on the x-axis.

⁹ See Appendix B for the data sets from the study by Dang et al. (2013)

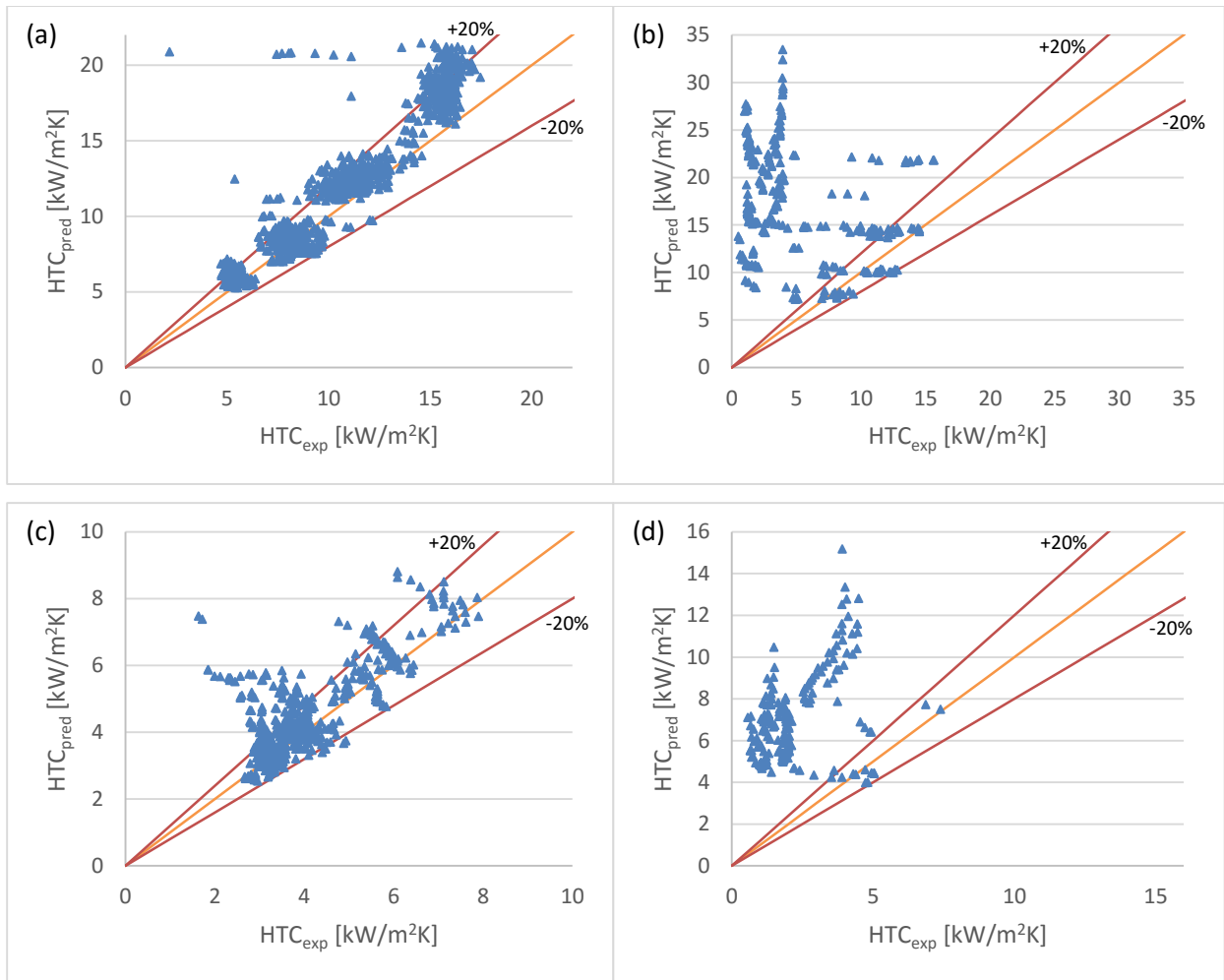


Figure 3.1: Comparison plots for conditions (a) to (d) of results by Aiyoshizawa

Plot (a) of Figure 3.1 is for pre-dryout conditions of the two-phase flow boiling process with no oil present in the system. For lower convection heat transfer coefficients there is a good correlation between the predicted coefficient and the experimental coefficient. For higher convection heat transfer coefficients however, the correlation by Aiyoshizawa over-predicts on average. Plot (b) of Figure 3.1 is for post-dryout conditions of the two-phase flow boiling process also with no oil present in the system. It is observed that over-prediction is a problem for the entire range of convection heat transfer coefficients considered. Plot (c) of Figure 3.1 is once again for pre-dryout conditions of the two-phase flow boiling process, but now with oil contamination and the calculations over-predict on average. Plot (d) of Figure 3.1 is for post-dryout conditions of the two-phase flow boiling process with oil contamination. Over-prediction is also observed here as in plot (b) where no oil is present, but for plot (d) the occurrence is more evident with less points lying close to the diagonal ($y = x$) line.

Table 3.1: Results summary for correlation by Aiyoshizawa

Conditions	Data points	MAD	MRD	20% Deviation
(a)	771	15.94%	12.29%	68.48%
(b)	267	569.28%	566.72%	15.73%
(c)	755	19.60%	15.44%	51.92%
(d)	182	303.27%	301.57%	6.04%

Table 3.1 gives a summary for the results of the calculations using the correlation by Aiyoshizawa when compared to the experimental data from Dang for the four plots shown in Figure 3.1. The correlation by Aiyoshizawa is most accurate for the parameters within which it was evaluated in the study by Li et al. (2014); that is, regions (a) and (c) for pre-dryout conditions, with and without oil contamination. For regions (b) and (d) however, under post-dryout conditions, the accuracy of the predictions by the correlation of Aiyoshizawa degenerates significantly. The positive percentage values for the MRD column of Table 3.1 indicate an over-prediction of the convection heat transfer coefficient on average. The correlation by Aiyoshizawa predicts pre-dryout convection heat transfer coefficients for flow boiling CO₂ with accuracies comparable to other existing correlations considered in Chapter 2 and may be used in calculations under these conditions.¹⁰ The correlation by Aiyoshizawa is however inaccurate when used for making predictions under post-dryout conditions and this study will therefore aim to develop a new convection heat transfer correlation in order to improve the accuracy of the predictions.

3.3 Summary

The theoretical background for this study was given. The experimental setup was explained and the evaluation approach was discussed. Assumptions made in the calculations were also listed. The two-phase flow boiling results obtained using the correlation by Aiyoshizawa were shown. It was observed that the correlation by Aiyoshizawa is adequate for the bounds within which it was evaluated in the study by Li et al. (2014); namely the pre-dryout region of two-phase flow boiling, both with and without oil contamination. Over-prediction of the convection heat transfer coefficient by the correlation of Aiyoshizawa occurs on average, especially for post-dryout conditions of two-phase flow. The correlation by Aiyoshizawa is therefore inadequate for predicting the convection heat transfer coefficient of flow boiling CO₂ over the entire vapour quality range. The next chapter describes the development of a new convection heat transfer coefficient correlation for CO₂ with improved accuracy which takes into account the effect of the OCR.

¹⁰ Refer to Table 2.4 for accuracies of some correlations compared to data sets from different sources.

CHAPTER 4

CORRELATION DEVELOPMENT AND VERIFICATION

The correlation by Aiyoshizawa was evaluated in the previous chapter by using the experimental data of Dang. The correlation was found to be inadequate for predicting the convection heat transfer coefficient of oil contaminated and uncontaminated CO₂ in the post-dryout region of two-phase flow boiling. It was decided that a new correlation should be developed to improve on the accuracy of the correlation by Aiyoshizawa.

This chapter will therefore focus on the development of a new correlation for predicting the two-phase flow boiling convection heat transfer coefficient for oil contaminated and uncontaminated CO₂. The previous chapter concluded that the correlation by Aiyoshizawa is sufficiently accurate for making predictions in the pre-dryout region of oil contaminated and uncontaminated CO₂. Both pre- and post-dryout calculation conditions will however be considered in the correlation development process of this chapter in order to obtain overall improved prediction accuracy.

First, the post-dryout phenomenon will be considered and its impact on the calculated predictions will be explained. Following the post-dryout phenomenon consideration, a new correlation for predicting the dryout vapour quality for the two-phase flow boiling of CO₂ will be presented and the improvement of the prediction results over the predictions by the correlation of Katsuta et al. (2008) will be shown. Next, the development of the new correlation for predicting the convection heat transfer coefficient will be detailed. The effect a new boiling suppression factors as well as newly developed curve modification factors on the accuracy of the convection heat transfer coefficient prediction for each of the different calculation conditions will be shown. Comparison will be made between the results obtained by the correlation of Aiyoshizawa and those obtained by the new correlation of this study for each of the calculation conditions.

4.1 Post-dryout phenomenon

In the previous chapter it was observed that the correlation by Aiyoshizawa is inaccurate for post-dryout predictions under both oil contaminated and uncontaminated conditions. Even though the correlation is sufficiently accurate for pre-dryout conditions when compared to the accuracies of other existing correlations for predicting the convection heat transfer coefficient¹¹, the degradation in accuracy in the post-dryout region limits its scope of usability.

¹¹ See Table 2.4 for reference.

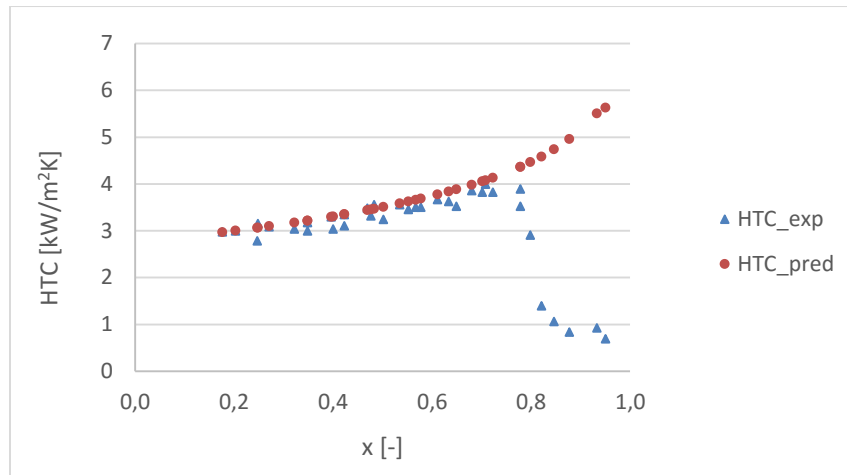


Figure 4.1: Experimental vs. predicted (Aiyoshizawa) convection HTC data: $q = 9$ [kW/m²], $G = 360$ [kg/m²s], $T_{\text{sat}} = 15$ [°C], $D = 2$ [mm], $\text{OCR} = 5\%$

Figure 4.1 is given for one of the 28 data sets from the study by Dang and shows the trend in the predicted data observed for all the data sets. It can be seen that the correlation by Aiyoshizawa predicts the convection heat transfer coefficient closely compared to the experimental coefficient up to the dryout point with only a small amount of over-prediction. At the dryout point a sudden decrease in the experimental convection heat transfer coefficient is observed while the predicted coefficient continues on the same trend it followed in the pre-dryout region, causing a divergence between the experimental and predicted data sets. This phenomenon is observed for all the data sets¹², for some to a greater extent than others, and significantly degrades the accuracy of the correlation by Aiyoshizawa in the post-dryout region. It is therefore desirable to find a new correlation to accurately predict the convection heat transfer coefficient in the post-dryout region for two-phase flow. To accomplish this, a new correlation for predicting the dryout vapour quality more accurately is first formulated in the following section.

4.2 New correlation for predicting the dryout vapour quality

The correlation by Katsuta for predicting the dryout point, equation (3.25), was used to find the dryout point for each of the 28 data sets. It was discovered that the correlation is not sufficiently accurate and in some instances a dryout quality greater than 1 was predicted, which is not physically possible.¹³ For the 28 data sets used in this study, the correlation by Katsuta had a MRD of 36.33%, indicating an over prediction on average, and a MAD of 44.60%. No other correlations were identified in literature that was suitable for predicting the dryout vapour quality during flow boiling of oil contaminated and uncontaminated CO₂.

¹² See Appendix B for the data sets obtained from Dang et al. (2013).

¹³ See Appendix C for the dryout vapour quality prediction data by the correlation of Katsuta et al. (2008).

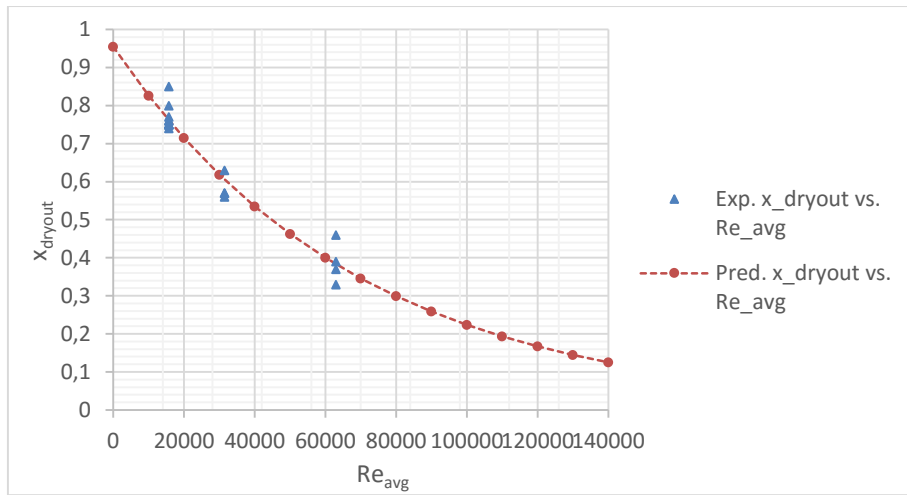


Figure 4.2: Dryout quality vs. average Reynolds number

By using experimental data available from the study by Dang¹⁴, a correlation was developed in this study which uses the average two-phase flow Reynolds number, Re_{avg} , and the reference diameter, D_{ref} . The newly proposed correlation for predicting the dryout vapour quality, x_{dryout} , for two-phase flow boiling of oil contaminated and uncontaminated CO₂ is as follows:

$$x_{dryout} = 0.9549 \times e^{-1.45 \times 10^{-5} \left(D_{ref} / D \right)^{1.5} Re_{avg}} \quad (4.1)$$

where $D_{ref} = 0.002$ is a constant with unit $[m]$ for non-dimensionality.

Figure 4.2 shows experimental dryout qualities for different average Reynolds numbers in the two-phase flow region of the 13 data sets with the reference diameter, D_{ref} . Three main clusters of experimental data are observed where the blue triangular markers are concentrated and a curve representing the predicted dryout vapour quality values is indicated by the red round markers and broken line. Equation (4.1) was obtained by fitting a trend line through the experimental data points. Equation (4.1) may be used to predict the dryout vapour quality for tube diameters varying from 0.002 $[m]$ to 0.006 $[m]$.

Table 4.1: Comparison between accuracies of dryout quality correlations

	Katsuta et al. (2008)	New correlation
Mean relative deviation (MRD):	36.33%	-1.45%
Mean absolute deviation (MAD):	44.60%	4.96%

¹⁴ See Appendix C for the dryout vapour quality experimental data by Dang and predicted values.

When tested against the total of 28 data sets from the study by Dang, the new correlation has a MRD of -1.45%, indicating a slight under-prediction on average, and a MAD of 4.96%. Both the MRD and MAD of the new correlation are significantly less than the MRD and MAD for the correlation by Katsuta. Table 4.1 gives a comparison between the accuracy of the new correlation and the correlation by Katsuta, from which the improvement is observable.

4.3 Convection heat transfer coefficient correlation development

The development of the new correlation for predicting the two-phase flow boiling convection heat transfer coefficient for oil contaminated and uncontaminated CO₂ is detailed in this section. The 28 data sets (containing 1975 data points) obtained from the study by Dang were used to develop the new correlation. It is important to note that all equations supplied for the new correlation are valid for the entire range of calculation conditions, as defined in Section 3.2.2, unless it is pertinently indicated when a specific equation is given that it is only valid for a particular calculation condition.

The new correlation uses equations (3.29) to (3.31) as well as equations (3.33) and (3.34). In order to improve on the prediction accuracy of the correlation by Aiyoshizawa, a new boiling suppression factor, S , was developed in this study from the experimental data. To accomplish this, focus was first given to calculation condition (a) where the pre-dryout region of the two-phase flow boiling process is considered with no oil contamination. Even though the S factor was developed using the data of calculation condition (a) it is used with appropriate modification (described at a later stage) for all other calculation conditions. S is based on the Re , Bo and Bd numbers as well as the previously defined reference diameter, D_{ref} . The Re , Bo and Bd numbers were specifically selected as input parameters for the equation of the S factor because these non-dimensional numbers take into account the effect of the viscosity, mass flux and surface tension respectively. The equation for the newly developed boiling suppression factor is:¹⁵

$$S = \left(-0.206 \ln \left(Re^{1.65} Bo^{0.2} Bd^{0.053} \right) + 3.55 \left(\frac{D}{D_{ref}} \right)^{0.0675} \right) \quad (4.2)$$

Calculations were done with the new S factor and Figure 4.3 shows the results comparison plot for the predicted convection heat transfer coefficient versus the experimental coefficient from the data by Dang. By comparing the plot of Figure 4.3 to plot (a) of Figure 3.1, the impact of the new S factor on the calculated results may be observed.

¹⁵ Refer to Appendix D for relevant data related to the development of the new factor equations of this study.

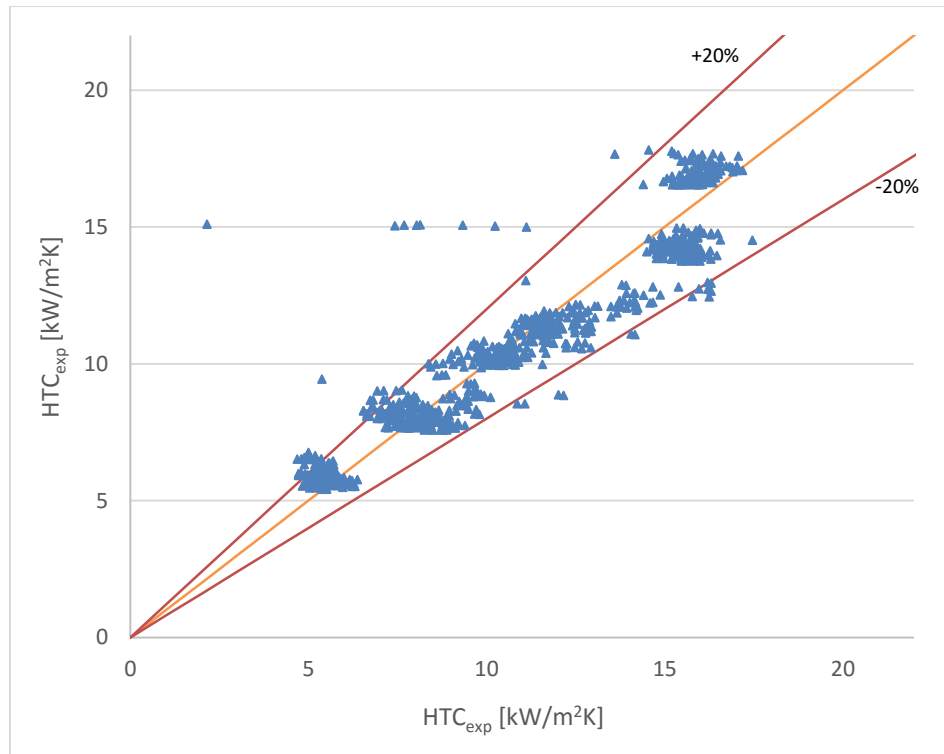


Figure 4.3: Results comparison - new suppression factor, calculation condition (a)

Table 4.2 compares the accuracy of the results by the correlation of Aiyoshizawa with that of the new correlation for calculation condition (a). Both the MAD and MRD for the new correlation using the new S factor show an improvement over the corresponding values by the correlation of Aiyoshizawa. Also, 83.40% of the 771 data points of calculation condition (a) fall within a 20% deviation of their experimental value for the new correlation with its new suppression factor, S , compared to 68.48% for the correlation by Aiyoshizawa.

Table 4.2: Results comparison: calculation condition (a)

	Aiyoshizawa	New Correlation
MAD	15.94%	9.42%
MRD	12.29%	0.66%
20% Deviation	68.48%	83.40%

The next step in the correlation development process was to consider calculation condition (c), the pre-dryout region of two-phase flow with oil contamination. Oil contamination significantly decreases the convection heat transfer coefficient in two-phase flow boiling of CO_2 . Figure 4.4 shows a plot comparing the experimental convection heat transfer coefficient for two data sets with the same parameters; $q = 9 \text{ [kW/m}^2\text{]}$, $G = 360 \text{ [kg/m}^2 \cdot \text{s]}$, $T_{\text{sat}} = 288 \text{ [K]}$, $D = 0.002 \text{ [m]}$,

and $L = 2[m]$ with the only difference between the data sets being whether or not oil is present in the two-phase flow boiling process. The red squares on the plot of Figure 4.4 indicate the experimental heat transfer coefficient data points for an $OCR = 0\%$ and the blue triangles indicate data points for an $OCR = 0.5\%$. The same trend of a decrease in the convection heat transfer coefficient caused by oil contamination can be observed for all the experimental data sets.¹⁶

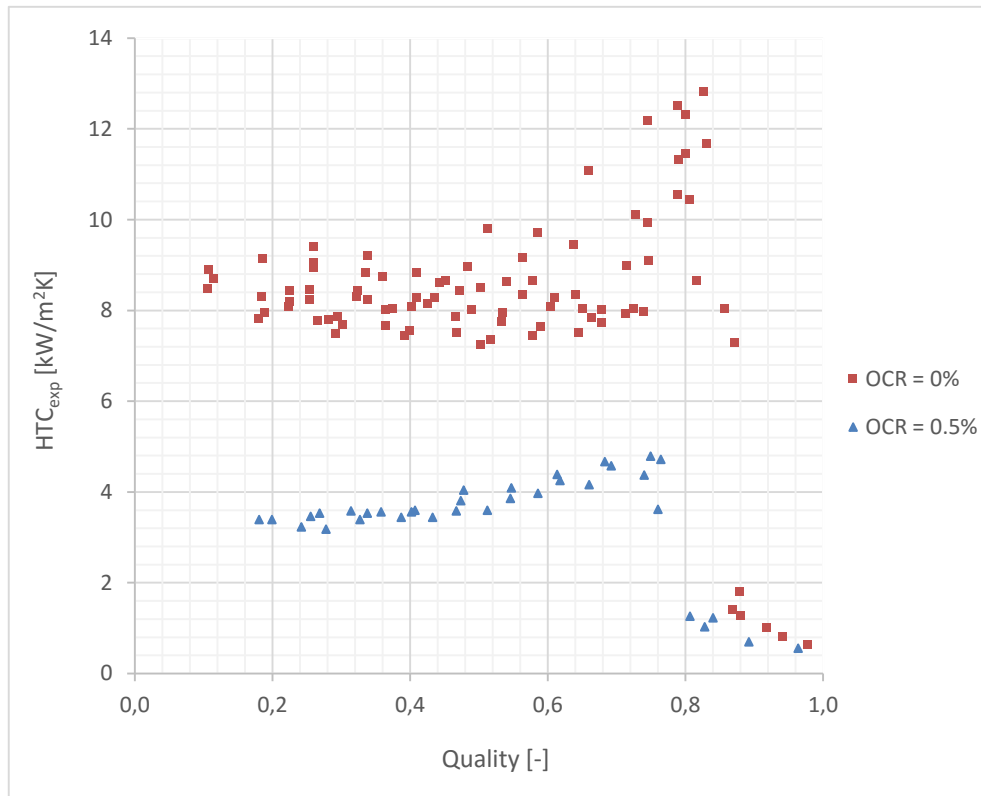


Figure 4.4: Effect of oil contamination on convection heat transfer coefficient

To compensate for the effect that oil contamination has on the convection heat transfer coefficient, an additional oil contamination boiling suppression factor, S_{oil} , was developed in this study. Calculation condition (c) was used for this part of the work, which considers the pre-dryout region of the two-phase flow boiling process of CO_2 with oil contamination. This changes the form of equation (4.2) to:

$$S = S_{oil} \left(-0.206 \ln \left(Re^{1.65} Bo^{0.2} Bd^{0.053} \right) + 3.55 \left(\frac{D}{D_{ref}} \right)^{0.0675} \right) \quad (4.3)$$

¹⁶ Refer to Appendix B for the experimental data sets by Dang et al. (2013).

Where S_{oil} is presented as:

$$S_{oil} = 1 \quad (4.4)$$

for uncontaminated CO_2 with $OCR = 0$, or as:

$$S_{oil} = 0.0087(OCR)^2 - 0.065(OCR) + 0.215 \left[0.675 \left(\frac{D}{D_{ref}} \right)^{-0.38} \left(\frac{G}{G_{ref}} \right)^{-0.2} \right] \quad (4.5)$$

for oil contaminated CO_2 with $OCR > 0$, where $G_{ref} = 720$ is a constant, with unit $\left[\text{kg}/\text{m}^2 \cdot \text{s} \right]$ for non-dimensionality.

Calculations were conducted incorporating the new factor S_{oil} with the factor S for the new correlation. Figure 4.5 shows the comparison plot for the predicted convection heat transfer coefficient versus the experimental coefficient from the data by Dang for calculation condition (c) after incorporating the new factor S_{oil} into the calculations. By comparing the plot of Figure 4.5 to plot (c) of Figure 3.1, the impact of the new oil contamination boiling suppression factor, S_{oil} , on the accuracy of the calculation results may be observed.

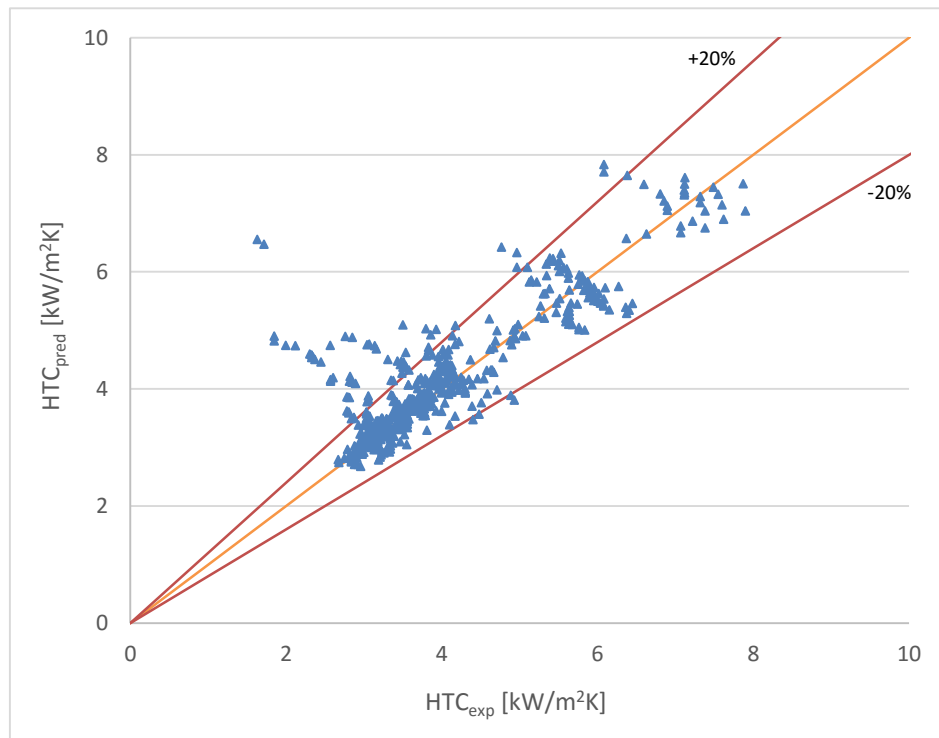


Figure 4.5: Results comparison - incorporation of new oil contamination suppression factor, calculation condition (c)

Table 4.3: Results comparison: calculation condition (c)

	Aiyoshizawa	New Correlation
MAD	19.60%	11.20%
MRD	15.44%	7.20%
20% Deviation	51.92%	61.46%

Table 4.3 compares the accuracy of the results by the correlation of Aiyoshizawa and the new correlation for calculation condition (c). Both the MAD and MRD for the new S factor and the new S_{oil} factor of the new correlation show an improvement over the corresponding values by the correlation of Aiyoshizawa. Also, 61.46% of the 755 data points of calculation condition (c) fall within a 20% deviation of the experimental value for the new correlation suppression factor, compared to 51.92% for the correlation by Aiyoshizawa. It is evident that the implementation of the new S and S_{oil} factors have improved the accuracy of calculation results for calculation conditions (a) and (c).

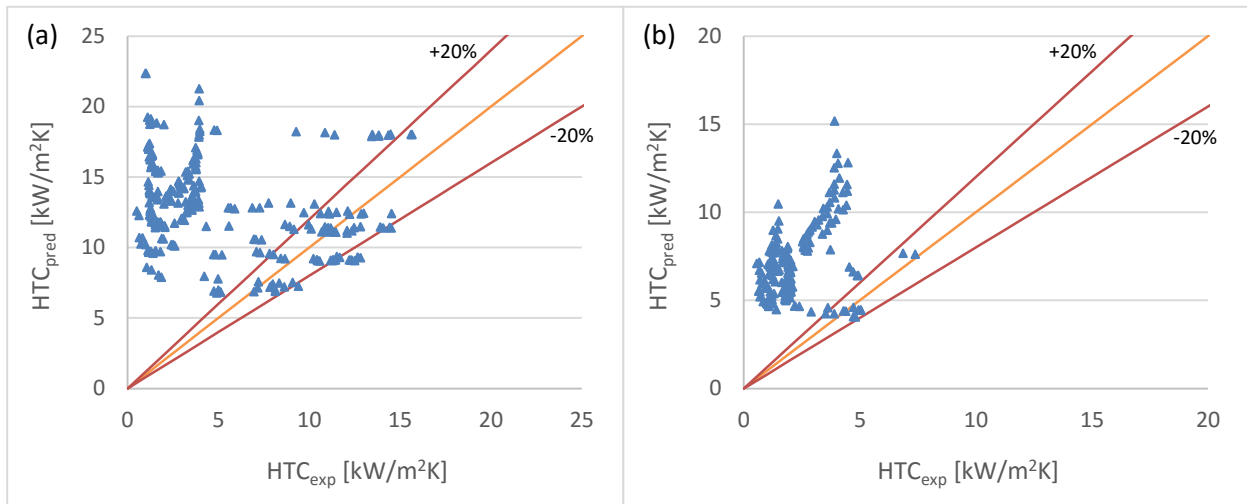


Figure 4.6: Results comparison - new suppression factors: plot (a) for calculation condition (b); and plot (b) for calculation condition (d)

Figure 4.6 shows the comparison plots for calculation conditions (b) and (d) following the implementation of the new S and S_{oil} factors. Investigating the effect of these factors on the calculation results for calculation conditions (b) and (d) however, reveal that the implementation of these factors alone do not sufficiently improve the accuracy of the results for these conditions. Calculation conditions (b) and (d) both consider the post-dryout region of two-phase flow boiling of CO₂, without and with oil contamination respectively.

From Figure 4.6 it is evident that there still exists a significant amount of over-prediction of the convection heat transfer coefficient for calculation conditions (b) and (d). The results for calculation conditions (b) and (d) when using the new suppression factors do however show a small amount of improvement over the results obtained from the correlation by Aiyoshizawa for the same conditions. Table 4.4 compares the accuracy of the results for calculation conditions (b) and (d) obtained from the correlation by Aiyoshizawa and from the new correlation using the new S and S_{oil} suppression factors.

Table 4.4: Results comparison: calculation conditions (b) and (d)

	Condition (b)		Condition (d)	
	Aiyoshizawa	New Correlation	Aiyoshizawa	New Correlation
MAD	569.28%	431.50%	303.27%	276.61%
MRD	566.72%	291.20%	301.57%	275.15%
20% Deviation	15.73%	19.48%	6.04%	6.04%

Table 4.4 shows improvements in the MAD and MRD for both calculation conditions (b) and (d), but the new correlation with the new suppression factors is still insufficiently accurate to be applied in calculations for making reliable predictions of the convection heat transfer coefficient under these conditions. In order to obtain improved prediction results with higher levels of accuracy, a curve modification factor, M , is introduced in the new correlation. The rationale behind the M factor is to modify the shape of the predicted convection heat transfer coefficient curve for a more accurate fit. A separate M factor for each of the calculation conditions (a) to (d) is proposed hereafter, as it was developed in this study from the experimental data obtained from Dang.

For calculation condition (a) where $x < x_{dryout}$ and $OCR = 0$:

$$M = 1 \quad (4.6)$$

The S factor of equation (4.3) was developed from the experimental data of Dang for calculation condition (a). Therefore the accuracy of the calculated predictions by the new correlation for calculation condition (a) when using only the new S factor in the calculations is considered adequate. For this reason no additional curve modification is required for calculation condition (a) and equation (4.6) of the M factor is equal to unity. The calculation results when incorporating equation (4.6) in the new correlation for predicting the convection heat transfer coefficient is consequently identical to the results shown in the plot of Figure 4.3. The result comparison for calculation condition (a) as shown in Table 4.2 also remain unchanged.

For calculation condition (c) where $x < x_{dryout}$ and $OCR > 0$:

$$M = a + bx^2 \quad (4.7)$$

where:

$$a = -0.0043ReBo + 0.9535 \quad (4.8)$$

$$b = 0.1851ReBo - 0.0483 \quad (4.9)$$

It was noted in Table 4.3 that for calculation condition (c) 61.46% of the predicted convection heat transfer coefficient data points by the new correlation incorporating the proposed S_{oil} factor fall within a 20% deviation of the experimental data points. This can be improved by using the M factor for calculation condition (c) represented by equation (4.7) in the convection heat transfer coefficient calculations. The values of both the MAD and MRD can also be reduced, indicating that better prediction accuracy is attained. Figure 4.7 shows the results comparison plot for calculation condition (c) when the M factor of equation (4.7) has been incorporated in the calculations.

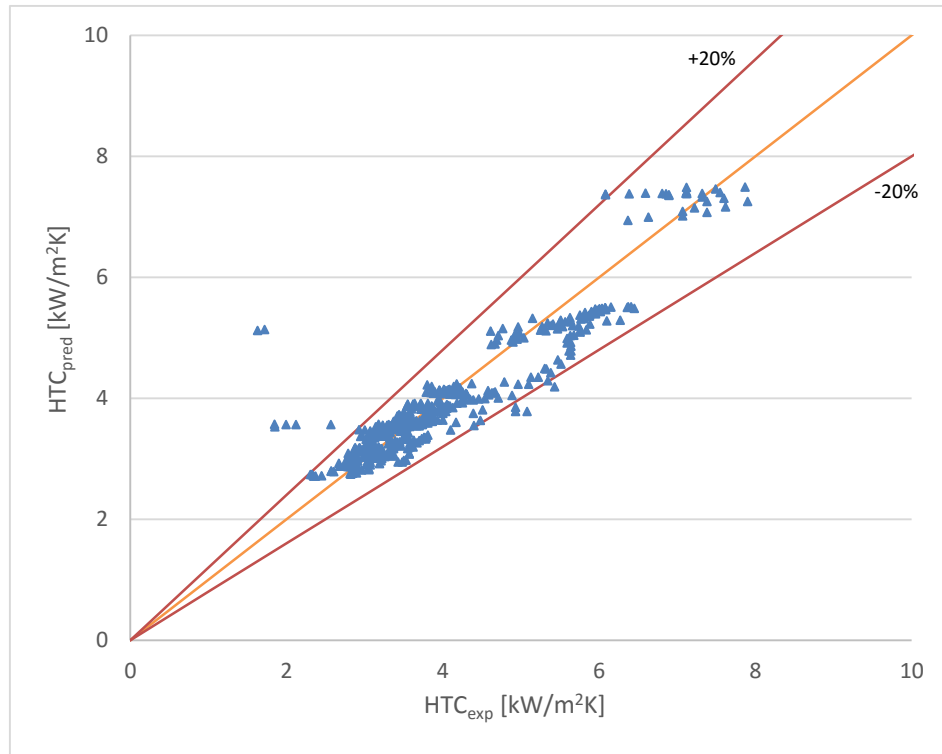


Figure 4.7: Results comparison - incorporation of curve modification factor, calculation condition (c)

When comparing the results shown in the plot of Figure 4.7 to those of Figure 4.5, the effect of the M factor on the results for calculation condition (c) can be observed. The points of the plot are slightly less scattered for Figure 4.7 than they were for Figure 4.5, indicating better prediction accuracy. By comparing plot (c) of Figure 3.1 to the plot of Figure 4.7, the total improvement in the prediction accuracy can be seen, showing the difference between the results obtained from the correlation by Aiyoshizawa and the new correlation using the S and M factors. Table 4.5 compares the accuracy of the results by three different correlations for calculation condition (c); the correlation of Aiyoshizawa, the new correlation with only the new S factors incorporated and the new correlation with the S and M factors incorporated.

Table 4.5: Results comparison: calculation condition (c) - M factor incorporated

	Aiyoshizawa	New Correlation (Only S factor)	New Correlation (S and M factors)
MAD	19.60%	11.20%	7.67%
MRD	15.44%	7.20%	0.92%
20% Deviation	51.92%	61.46%	80.79%

For calculation condition (b) where $x > x_{dryout}$ and $OCR = 0$:

$$M = \frac{1}{\left(e^{-200x_{corrected}^2} + 0.2x_{corrected}^{0.5} \right)} \quad (4.10)$$

where:

$$x_{corrected} = x - x_{dryout} \quad (4.11)$$

Table 4.4 shows the accuracy of the new correlation with only the S factors incorporated for calculation condition (b). Both the MAD and MRD for calculation condition (b) are very high and only 19.48% of the predicted convection heat transfer coefficient data points fall within a 20% deviation from their experimental value. The M factor represented by equation (4.10) was developed from the 267 experimental data points from Dang for calculation condition (b) in order to improve the prediction accuracy. A corrected vapour quality, $x_{corrected}$, (equation (4.11)) is used in the calculation of the M factor for calculation condition (b) and (d) because the post-dryout region of the two-phase flow boiling process is considered. Figure 4.8 shows the results comparison plot for calculation condition (b) when the M factor of equation (4.10) has been incorporated.

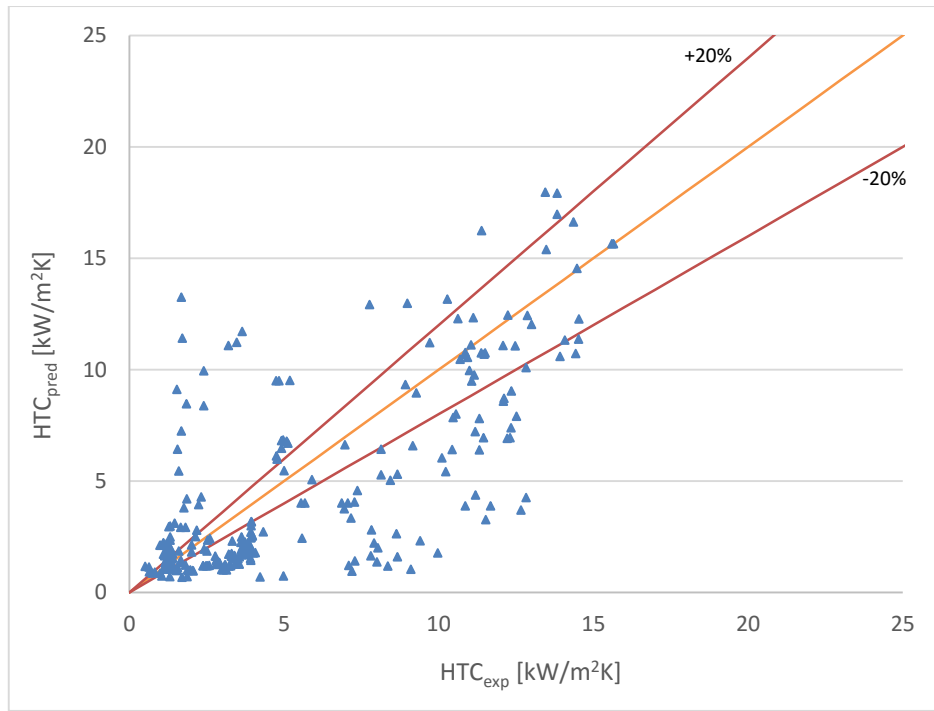


Figure 4.8: Results comparison - incorporation of curve modification factor, calculation condition (b)

By comparing the plot of Figure 4.8 to plot (a) of Figure 4.6, the difference in the prediction results can be observed when the M factor of equation (4.10) is implemented. Plot (a) of Figure 4.6 illustrates the results comparison of calculation condition (b) for calculations by the new correlation when only the new S factors are incorporated. Comparison of the plot of Figure 4.8 to plot (b) of Figure 3.1 shows an improvement in the prediction results between the correlation of Aiyoshizawa and the new correlation using the new S and M factors. The reason for the large number of scattered data points will be addressed in the next section. Table 4.6 compares the accuracy of the results by three different correlations for calculation condition (b); the correlation of Aiyoshizawa, the new correlation with only the new S factors incorporated and the new correlation with the S and M factors incorporated. A definite improvement is observed between the correlation of Aiyoshizawa and the new correlation.

Table 4.6: Results comparison: calculation condition (b) - M factor incorporated

	Aiyoshizawa	New Correlation (Only S factor)	New Correlation (S and M factors)
MAD	569.28%	431.50%	52.05%
MRD	566.72%	291.20%	1.42%
20% Deviation	15.73%	19.48%	26.97%

For calculation condition (d) where $x > x_{dryout}$ and $OCR > 0$:

$$M = \frac{1}{[(slope)(x_{corrected}) + intercept]} \quad (4.12)$$

where: $slope = -19 + (-6.3 \times 10^{-5}) Re + 2 \ln(Re) + 0.15 \quad (4.13)$

$$intercept = 0.79 + \frac{-4.4}{\ln(Re)} \quad (4.14)$$

Table 4.4 shows the accuracy of the new correlation with only the S factors incorporated for calculation condition (d) and no great improvement in the prediction accuracy is observed when compared to the accuracy of the correlation by Aiyoshizawa for the same calculation condition. There is only a slight improvement in the values of the MAD and MRD while the 6.04% of predicted data points falling within a 20% deviation of their experimental values remains unchanged. The M factor of equation (4.12) was developed in this study from the 182 experimental data points from Dang which fall under calculation condition (d). Figure 4.9 shows the results comparison plot for calculation condition (d) with the M factor of equation (4.12) incorporated.

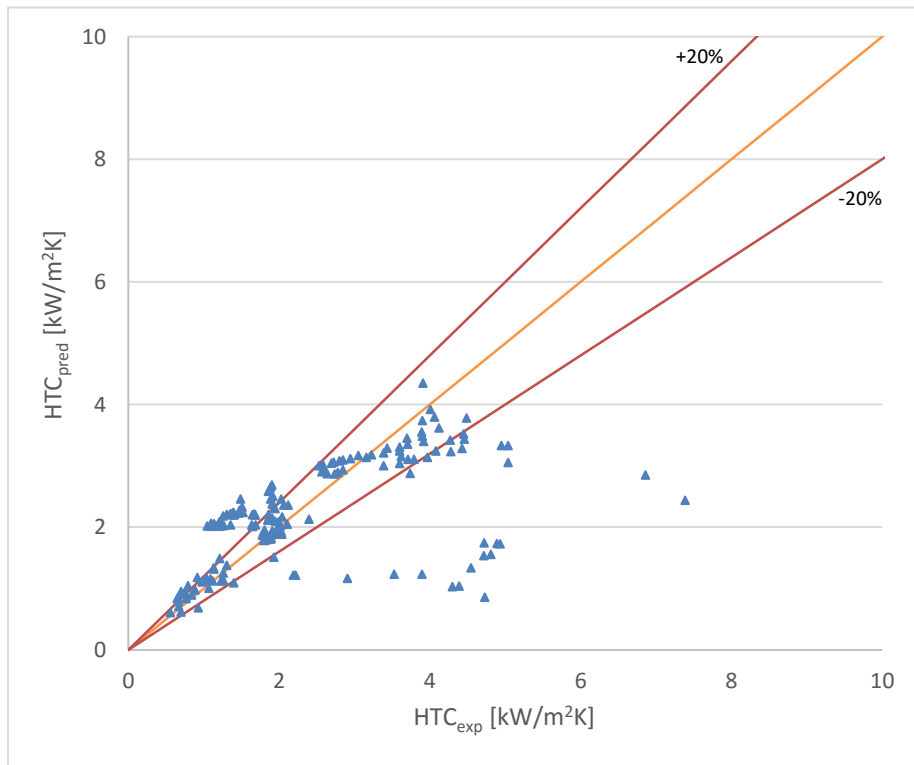


Figure 4.9: Results comparison - incorporation of curve modification factor, calculation condition (d)

By comparing the plot shown in Figure 4.9 to plot (b) of Figure 4.6, the difference in the predicted results can be observed for when the M factor of equation (4.12) is implemented in calculation condition (d). Plot (b) of Figure 4.6 shows the results comparison for the new correlation when only the new S factors are incorporated in the calculations, with the M factor of equation (4.12) not yet used. Comparison of the plot of Figure 4.9 to plot (d) of Figure 3.1 shows an improvement in the prediction results between the correlation of Aiyoshizawa and the new correlation using both the new S and M factors. Table 4.7 compares the accuracy of the results by three different correlations for calculation condition (b); the correlation of Aiyoshizawa, the new correlation with only the new S factors incorporated and the new correlation with the S and M factors incorporated. A marked improvement in the accuracy of the results is observed between the correlation of Aiyoshizawa and the new correlation using the new S and M factors for calculation condition (d).

Table 4.7: Results comparison: calculation condition (d) - M factor incorporated

	Aiyoshizawa	New Correlation (Only S factor)	New Correlation (S and M factors)
MAD	303.27%	276.61%	26.58%
MRD	301.57%	275.15%	-0.54%
20% Deviation	6.04%	6.04%	55.49%

The final form for the equation of the total two-phase convection heat transfer coefficient, h_{tp} , of the new correlation for calculation conditions (a) to (d) is:¹⁷

$$h_{tp} = \frac{Fh_{cb} + Sh_{nb}}{M} \quad (4.15)$$

where h_{cb} is the convective boiling component and h_{nb} is the nucleate boiling component. The factors F and S are the convective enhancement factor and boiling suppression factor respectively. The M factor, which is a unique contribution made by this study, is the curve modification factor and distinguishes equation (4.15) from equation (3.28).

4.4 Results summary - new heat transfer coefficient correlation

Section 4.3 detailed the development of the new convection heat transfer coefficient correlation of this study. Attention was given to the impact of the newly introduced S and M factors on the

¹⁷ Refer to Appendix E for the complete set of equations for the new correlation developed in this study.

accuracy of the calculated predictions for each of the calculation conditions (a) to (d) described in Section 3.2.2. Result comparison plots were given with the introduction of each of the new factors to show how the new factor improved the accuracy of the convection heat transfer coefficient prediction. This section will give a summary of the results by the new correlation. Result comparison plots will be shown and prediction accuracies will be tabulated for ease of reference when compared to result accuracies of the correlation by Aiyoshizawa shown in Chapter 3.

The 28 data sets from the study by Dang used in Chapter 3 to evaluate the correlation by Aiyoshizawa, are also used for the evaluation of the new correlation developed in this study. The same comparison plots for the four calculation conditions (a) to (d) will also be used here to assess the accuracy of the new correlation. By using the same comparison plots, a clearer demonstration of the improvement in accuracy of the new correlation over the correlation by Aiyoshizawa may be presented and it will be possible to quantify the improvement.

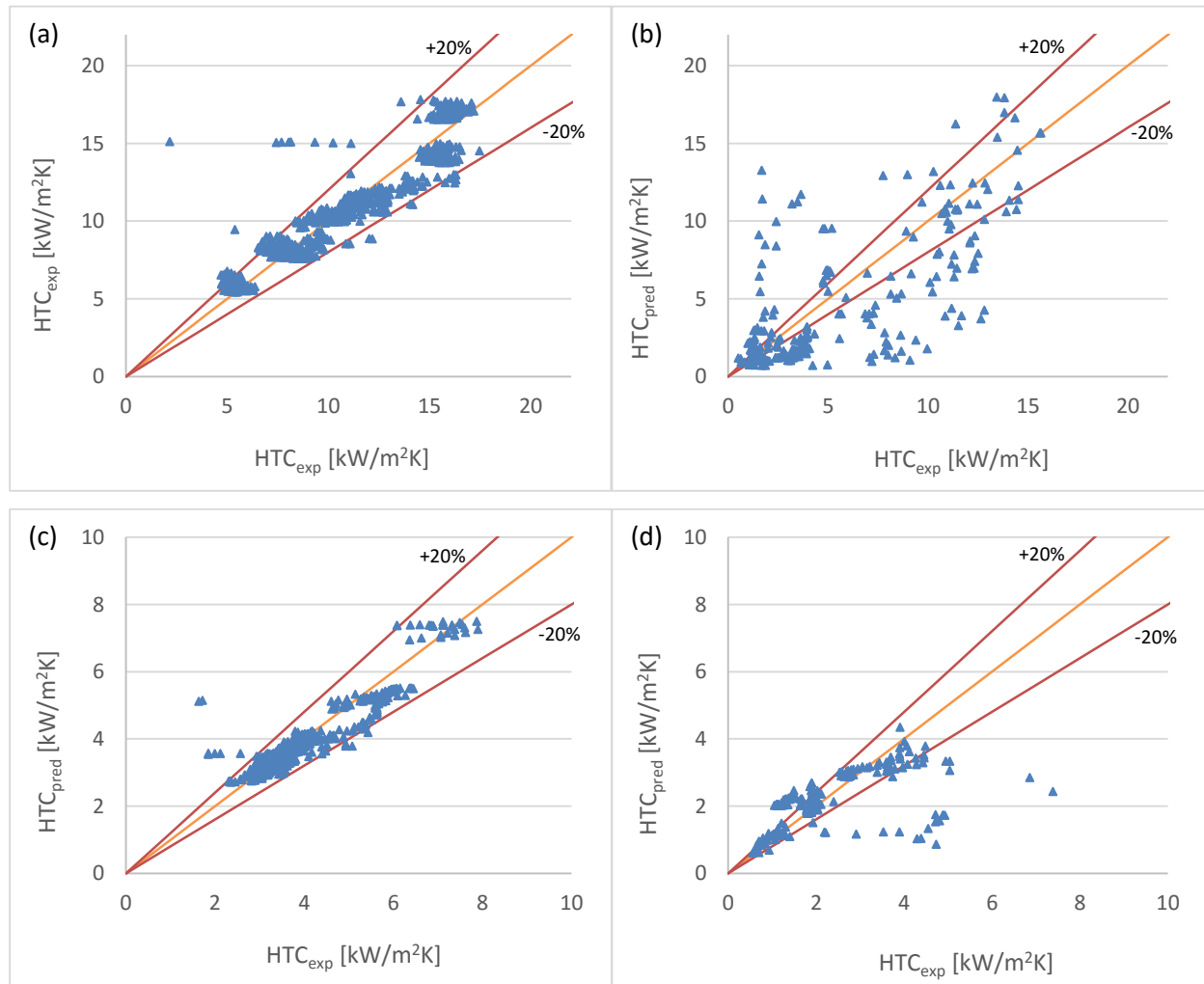


Figure 4.10: Results comparison - calculation conditions (a) to (d) - new correlation

Figure 4.10 shows the results comparison plots for calculation conditions (a) to (d) of the new correlation with the S and M factors incorporated in the calculations. Figure 3.1 shows the same results comparison plots for calculation conditions (a) to (d) by the correlation of Aiyoshizawa. By comparing the plots of Figure 4.10 to the corresponding plots of Figure 3.1, it is evident that the new correlation predicts the convection heat transfer coefficients better than the correlation of Aiyoshizawa for all four the calculation conditions.

Table 4.8: Results summary - Correlation by Aiyoshizawa vs. new correlation

Calculation Condition	Data points	Correlation by Aiyoshizawa			New Correlation		
		MAD	MRD	20% Deviation	MAD	MRD	20% Deviation
(a)	771	15.94%	12.29%	68.48%	9.42%	0.66%	83.40%
(b)	267	569.28%	566.72%	15.73%	52.05%	1.42%	26.97%
(c)	755	19.60%	15.44%	51.92%	7.67%	0.92%	80.79%
(d)	182	303.27%	301.57%	6.04%	26.58%	-0.54%	55.49%

Table 4.8 compares the accuracy of the results obtained by the correlation of Aiyoshizawa to the accuracy of the results obtained by the new correlation of this study when the new S and M factors are incorporated in the calculations. A noticeable improvement is evident in the MAD for all four regions indicating a higher degree of accuracy for the predictions by the new correlation over the predictions made by the correlation of Aiyoshizawa. The MRD for all four regions is also smaller, with the greatest improvement observed for calculation conditions (b) and (d), showing that the average amount of over- and under-prediction has been reduced.

When studying Table 4.8, notice the higher MAD values for calculation conditions (b) and (d). This is due to the scattered nature of the comparison plot data points for these calculation conditions, as can be seen from plots (b) and (d) of Figure 4.10. The scattered nature of the comparison plot data points of calculation conditions (b) and (d) was determined to be as a result of the uncertainty present in the prediction of the dryout vapour quality by the new dryout vapour quality correlation of this study given by equation (4.1). Referring to Table 4.1, the MAD of the new correlation used to predict the dryout vapour quality when applied to the experimental data of Dang is 4.96%. This can be interpreted as a plus or minus 4.96% interval within which the predicted dryout vapour quality falls from its actual experimental value, referred to as the uncertainty interval in this study. It can also be explained as a plus or minus 0.0496 quality range surrounding the actual experimental dryout vapour quality value for each experimental data set, where an error in the predicted convection heat transfer coefficient is more likely because of the potential error in the dryout vapour quality prediction.

Figure 4.11 shows how the predictions for calculation conditions (a) to (d) are affected when the dryout vapour quality correlation uncertainty interval is omitted from calculations by the new convection heat transfer coefficient correlation. By comparing the plots of Figure 4.10 to the corresponding plots of Figure 4.11, it can be seen that the amount of scattered data has been reduced by omitting the dryout vapour quality correlation uncertainty interval. This proves that the uncertainty interval of the dryout vapour quality correlation has a definite effect on the calculation accuracy of the new convection heat transfer coefficient correlation of this study.

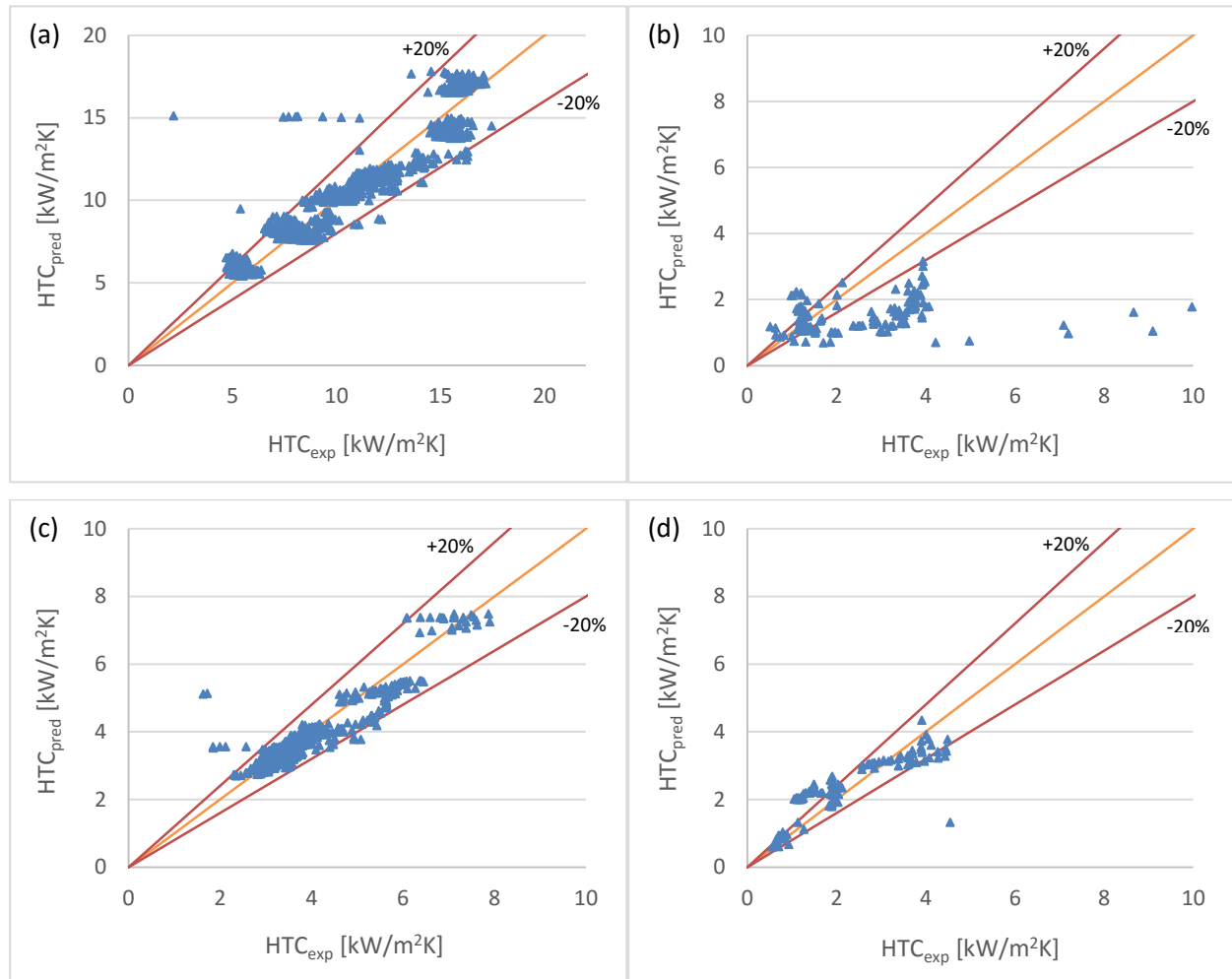


Figure 4.11: Results comparison for new correlation - uncertainty interval omitted

Table 4.9 shows the difference between the results obtained from calculations by the new correlation of this study for the entire vapour quality range and the results obtained by the new correlation of this study with the dryout vapour quality correlation uncertainty interval omitted. This is done only to show the effect of the uncertainty interval on the accuracy of the results. The uncertainty interval should never be omitted when the new correlation is used to perform heat transfer coefficient calculations.

Table 4.9: Results summary for new correlation - uncertainty interval omitted

	New Correlation (Entire vapour quality range)				New Correlation (Uncertainty interval omitted)			
Calculation Condition	Data points	MAD	MRD	20% Deviation	Data points	MAD	MRD	20% Deviation
(a)	771	9.42%	0.66%	83.40%	723	9.42%	0.66%	86.86%
(b)	267	52.05%	1.42%	26.97%	135	40.42%	-11.99%	26.27%
(c)	755	7.67%	0.92%	80.79%	675	7.67%	0.92%	83.85%
(d)	182	26.58%	-0.54%	55.49%	102	21.63%	13.41%	55.88%

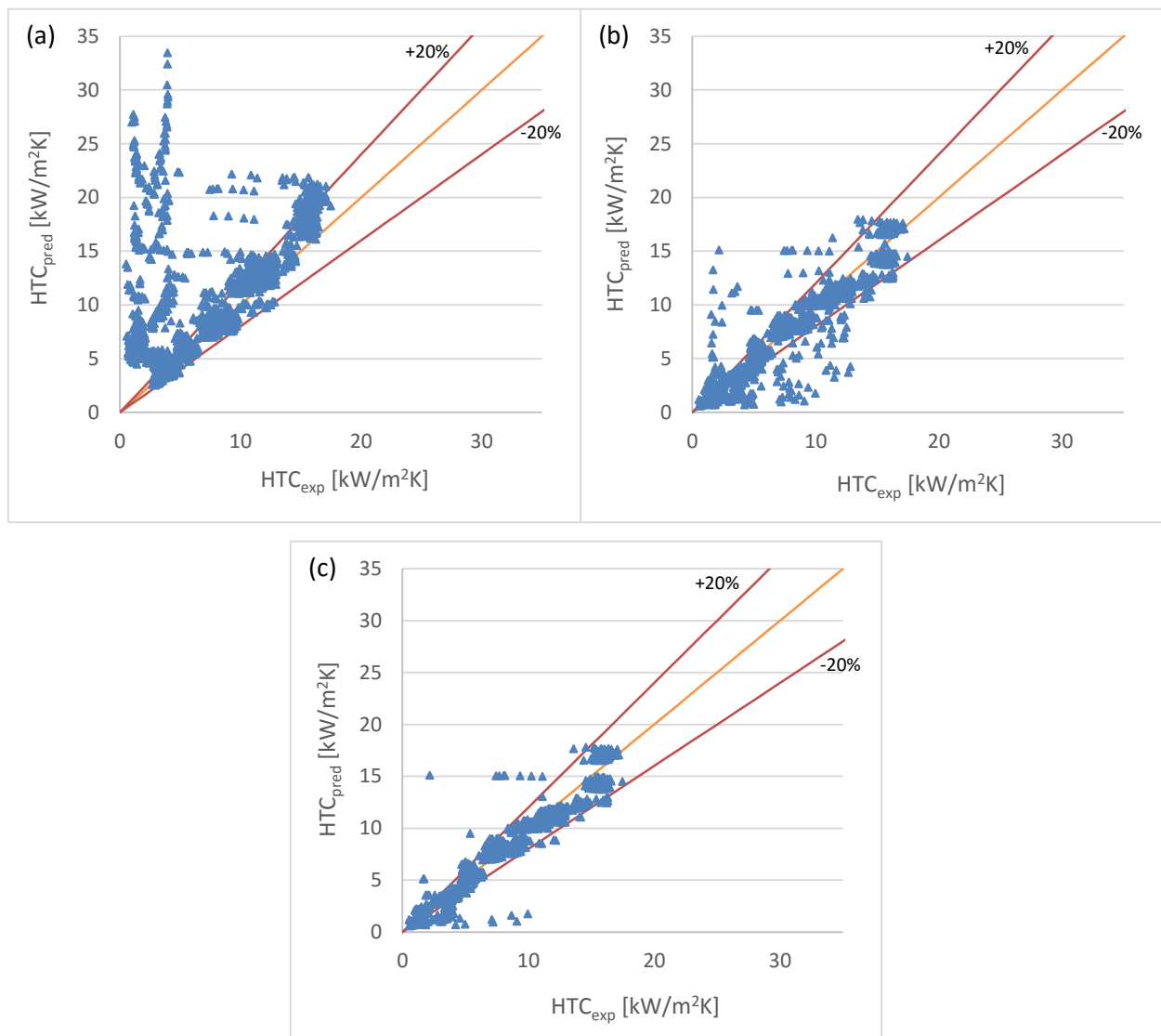


Figure 4.12: Convection heat transfer coefficient comparison plots for the results of the complete data set; (a) Aiyoshizawa et al. (2006), (b) New correlation, (c) New correlation with uncertainty interval omitted

Plot (a) of Figure 4.12, which shows the results comparison for the correlation by Aiyoshizawa, has a problem with over-prediction. This is due to the inability of the correlation by Aiyoshizawa to take into account the effect of the dryout phenomenon and its inaccuracy in predicting the convection heat transfer coefficient under post-dryout conditions. The new correlation, of which the results comparison are shown in plot (b) of Figure 4.12, attempts to overcome this problem by introducing a new correlation for predicting the dryout vapour quality. The effect of which is an improvement in accuracy that can be observed by comparing plot (a) to plot (b) and by considering the results summary of Table 4.8. Some scatter is present in the post-dryout region, due to the new dryout vapour quality correlation uncertainty interval. Plot (c) shows the results for the new correlation where the dryout vapour quality correlation uncertainty interval has been omitted. The omission serves only to demonstrate the effect of the uncertainty interval on the prediction accuracy of the new convection heat transfer coefficient correlation and it should not be done when performing calculations using the correlation.

Table 4.10 contains a summary for the results and the new correlation, as developed in this study, shows a notable improvement in accuracy over the correlation presented by Aiyoshizawa.

Table 4.10: Results summary: complete data sets, Aiyoshizawa and new correlation

Data	Data points	MAD	MRD	20% Deviation
Aiyoshizawa et al. (2006)	1975	118.62%	115.11%	49.27%
New correlation	1975	16.10%	0.75%	72.20%

4.5 Summary

This chapter focussed on the new correlations developed in this study. The post-dryout phenomenon was described and a new correlation for predicting the dryout vapour quality was given. The new correlation developed in this study for predicting the flow boiling convection heat transfer coefficient of oil contaminated and uncontaminated CO₂ was presented and the development process was explained. The impact of the new S and M factors on prediction accuracy was also shown and results obtained from calculations made using the new convection heat transfer coefficient correlation were compared to experimental results by Dang. It was determined that the new correlation shows an improvement in accuracy over the correlation by Aiyoshizawa. The MAD improved from 118.62% to 16.10% and the MRD improved from 115.11% to 0.75% while 72.20% of the predictions by the new correlation fall within a 20% deviation of their corresponding experimental values compared to the 49.27% by the correlation of Aiyoshizawa. The dryout vapour quality correlation uncertainty interval was also explained and its effect on the prediction accuracy of the new convection heat transfer coefficient correlation was shown.

CHAPTER 5

CONCLUSION

This study focussed on the investigation of existing correlations for predicting the flow boiling convection heat transfer coefficients of oil contaminated and uncontaminated CO₂. Emphasis was placed on oil contaminated CO₂ and the correlations considered for investigation in this study had to take into account the effect of the OCR on convection heat transfer. A literature review was conducted in which the most suitable existing correlations were identified. From the correlation evaluation by Li et al. (2014) it was established that the correlation of Aiyoshizawa et al. (2006) was the most accurate among those considered for predicting the convection heat transfer coefficient for oil contaminated and uncontaminated CO₂ under flow boiling conditions.¹⁸

Some previous studies have been conducted by other researchers to gather experimental data for the flow boiling convection heat transfer coefficient of oil contaminated and uncontaminated CO₂. The data from the study by Dang et al. (2013) was selected for use in this study because it is the largest available data set from a single source, containing a total of 1975 data points.

The Aiyoshizawa et al. (2006) correlation was evaluated against the experimental data obtained from the study by Dang et al. (2013). It was found that the Aiyoshizawa correlation has a MAD of 118.62% and a MRD of 115.11%, with 49.27% of the predicted data points falling within a 20% deviation of their corresponding experimental values when compared to the total data set of Dang. It was established that the high MAD and MRD values for the correlation by Aiyoshizawa is due to the large amount of over prediction observed under post-dryout conditions of the two-phase flow boiling process for both oil contaminated and uncontaminated CO₂.¹⁹ A new convection heat transfer coefficient correlation was subsequently developed in this study to improve on the prediction accuracy of the evaluated correlation of Aiyoshizawa et al. (2006).

It was required to first find a means to accurately predict the dryout vapour quality in order to successfully develop a new correlation for predicting the convection heat transfer coefficient. A correlation by Katsuta et al. (2008) for predicting the dryout vapour quality was the only suitable correlation identified from literature and it was evaluated against the experimental data of Dang and found to have a MAD of 44.60% and a MRD of 36.33%. Following evaluation, it was decided that the correlation of Katsuta et al. (2008) for predicting the dryout vapour quality was not sufficiently accurate and a new correlation for this purpose was developed from the experimental

¹⁸ See Table 2.4 for correlation accuracies when tested against different data sets from Li et al. (2014).

¹⁹ See Table 3.1 for MAD and MRD values for different calculation conditions by correlation of Aiyoshizawa.

data of Dang. The new correlation was found to have a MAD of 4.96% and a MRD of -1.45%, which showed an improvement in accuracy over the correlation by Katsuta et al. (2008).

Once a more accurate correlation for predicting the dryout vapour quality was available, a new correlation for the flow boiling convection heat transfer coefficient of oil contaminated and uncontaminated CO₂ could be developed. The development process of the new correlation along with its new boiling suppression factor, S , the new oil contamination boiling suppression factor, S_{oil} , and the new curve modification factors, M , for each of the calculation conditions of this study was explained. The influence of each of these new factors on the accuracy of the predictions compared to the experimental data of Dang was shown and the improvement in accuracy over the predictions by the correlation of Aiyoshizawa for each of the calculation conditions was also given.²⁰ It was found that the new correlation developed in this study has a MAD of 16.10% and a MRD of 0.75% with 72.20% of the predicted data points falling within a 20% deviation of their corresponding experimental values when compared to the entire data set of Dang.²¹

The final part of this study considers the uncertainty interval of the new dryout vapour quality correlation and shows the impact that it has on the prediction accuracy of the new convection heat transfer coefficient correlation of this study. The influence of the uncertainty interval on the accuracy of the convection heat transfer coefficient prediction was also demonstrated.

RECOMMENDATIONS FOR FURTHER STUDY:

This study identified some aspects which potentially merits further study, but have not been included in this study. Recommendations regarding these aspects include:

- The new correlation for predicting the two-phase convection heat transfer coefficient for oil contaminated and uncontaminated CO₂ should be tested against experimental data sets other than those of Dang et al. (2013) used in this study, to determine whether or not the correlation maintains its accuracy outside the parameter range of the data used to develop it.
- The new dryout vapour quality correlation developed in this study should be improved in order to attain better prediction accuracy. A greater understanding of the dryout phenomenon of flow boiling oil contaminated and uncontaminated CO₂ will have to be achieved in order to accomplish this.

²⁰ See Table 4.8 for a comparison between the accuracies of the correlation by Aiyoshizawa et al. (2006) and the new convection heat transfer coefficient correlation.

²¹ See Table 4.10 for a comparison between the accuracies of the correlation by Aiyoshizawa et al. (2006) and the new convection heat transfer coefficient correlation when compared to the total data set of Dang et al. (2013).

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APPENDIX A: CORRELATION EES CODES

This section starts off by presenting the control volume used in the EES calculations of this study. Certain key ideas are explained in order to make it possible for readers with no EES experience to understand the logic behind the calculations. By using the control volume shown in this section and the correlations explained in the text of this study, it will be possible for any reader to perform the necessary calculations in order to duplicate the results. The EES codes for the correlation by Aiyoshizawa and the correlation developed in this study are also presented.

Graphical Representation of Control Volumes used in EES Calculations:

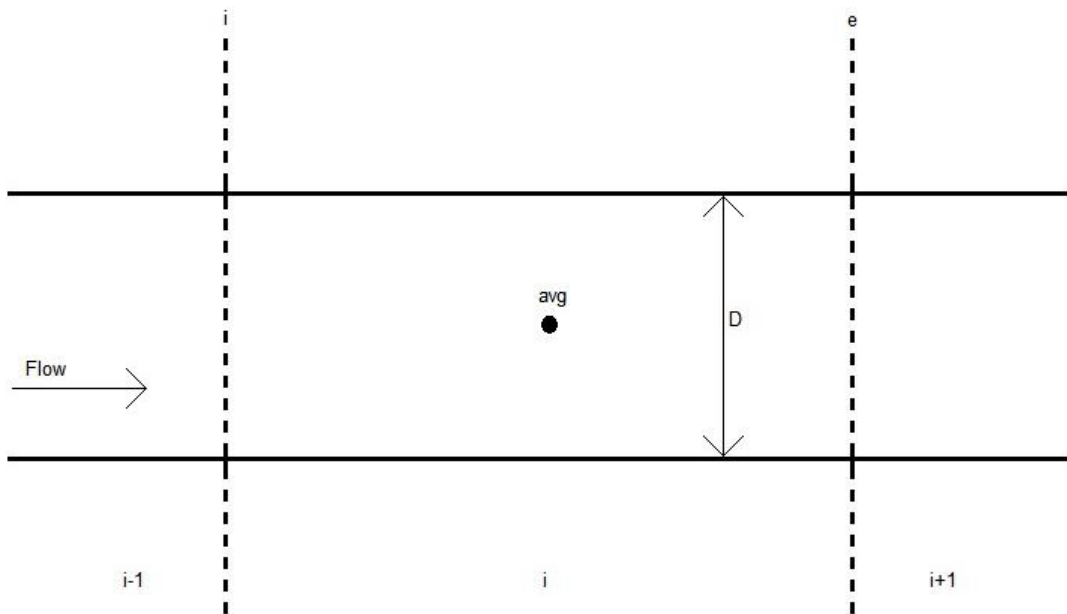


Figure A. 1: Tube incremental control volume used in EES calculations

Figure A.1 shows the incremental control volume of the generic heat exchanger tube used in the calculations of this study. The inlet of the control volume is denoted by i and the exit of the control volume is indicated with e . The average value of certain properties are needed for some calculations and these are obtained by taking the average of the properties at the inlet and exit of the increment and these are denoted by avg . The flow direction is indicated in Figure A.1 along with the diameter of the tube, D . The EES code makes use of an iterative calculation methodology and the control volume under consideration for each iteration is called control volume i , the control volume of the previous iteration by $i-1$ and the control volume of the next iteration by $i+1$. The generic heat exchanger tube is divided into $N = 100$ equal vapour quality increments from 0 to 1.

The Calculation Procedure:

The following constant input parameters need to be specified in order for the calculations of both correlations to be successfully performed:

1. Oil Concentration Ratio (OCR)
2. Vapour quality at heat exchanger tube inlet (x_i)
3. Saturation temperature (T_{sat})
4. Constant mass flux (MassFlux)
5. Constant heat flux (HeatFlux)
6. Vapour quality at heat exchanger tube outlet (x_e)
7. The pipe geometry, diameter (D) and length (L)
8. The gravitational constant acceleration (g)
9. The number of equal vapour quality increments (N)

Once all these constant input parameters have been specified, the thermodynamic properties at the inlet and outlet of the heat exchanger tube test section have to be calculated. The EES programs make use of the built in EES functions to find these values, but thermodynamic property tables for R744 can be used if a different software package than EES is chosen to perform the calculations. The thermodynamic properties determined at the inlet and outlet of the heat exchanger tube test section are:

1. Pressure (P)
2. Enthalpy (h)
3. Viscosity (μ)
4. Constant pressure specific heat (Cp)
5. Density (ρ)
6. Conductivity (λ)
7. Surface tension (σ)

Next, calculations are performed to calculate the pipe geometry. The wall surface area (A_{wall}) of the tube is calculated using equation (3.16) as well as the cross-sectional flow area (A_{flow}) of the tube with equation (3.14). The total heat transfer rate for the entire length of the tube (Q_{total}) is calculated thereafter using equation (3.15) from which the incremental heat transfer rate (Q_{inc}) may also be calculated by equation (3.17). Finally, the mass flow rate ($\dot{m}$) is calculated with equation (3.13).

The next step is to initialize a duplicate which calculates the average thermodynamic properties of each of the equal vapour quality increments of the tube between the inlet and the outlet. First however, the average vapour quality ($x_{avg}[i]$) of each increment is calculated. The average enthalpy value ($h_{avg}[i]$) of each vapour quality increment is also determined. The average thermodynamic properties of each of the equal vapour quality increments of the heat exchanger tube test section which are calculated are:

1. Average dynamic viscosity ($\mu[i]$)
2. Average density ($\rho[i]$)
3. Average kinematic viscosity ($\nu[i]$)
4. Average constant pressure specific heat ($c_p[i]$)
5. Average conductivity ($\lambda[i]$)

Lastly, the average fluid flow velocity ($V[i]$) for the increment $[i]$ is also determined along with the average fluid bulk temperature ($T_{B[i]}$) of the increment.

The procedure implementing either the correlation of Aiyoshizawa or the new correlation of this study is then called. These procedures use the thermodynamic properties and other parameters calculated previously to calculate the flow-boiling convection heat transfer coefficient of the oil contaminated carbon dioxide in the heat exchanger test tube section.

If the procedure for the correlation of Aiyoshizawa is called, equations (3.28) to (3.35) are used. If however the new correlation of this study is used, the procedure uses equations (4.2) to (4.15). The implementation of the new correlation is slightly more complex to implement as different S and M factors are used depending on whether the CO_2 -oil mixture is in the pre- or post-dryout state and also on whether the $\text{OCR}=0$ or if the $\text{OCR}>0$. The four scenarios of equation implementation for the new correlation is as follows:

1. If ($x < x_{\text{dry}}$) and ($\text{OCR}>0$) then, implement equations (4.7) to (4.9).
2. If ($x > x_{\text{dry}}$) and ($\text{OCR}>0$) then, implement equations (4.12) to (4.14).
3. If ($x < x_{\text{dry}}$) and ($\text{OCR}=0$) then, implement equation (4.6).
4. If ($x > x_{\text{dry}}$) and ($\text{OCR}=0$) then, implement equation (4.10).

The procedures for both the correlation of Aiyoshizawa and the new correlation return a calculated value for the average flow-boiling convection heat transfer coefficient for the specific vapour quality increment $[i]$ for which it was called. This value is automatically stored in an array table by EES. A lookup table is then created by EES which uses interpolation techniques to find the corresponding calculated heat transfer coefficient for each of the available experimental heat transfer coefficients from the data of Dang at its specific vapour quality point for the specified set of input parameters. By doing this a lookup table is created where the experimental value of the heat transfer coefficient from Dang ($\text{HTC}_{\text{exp}}[i]$) at a specific experimental vapour quality point ($x_{\text{exp}}[i]$) can be compared with the calculated predicted heat transfer coefficient ($\text{HTC}_{\text{pred}}[i]$) by either the correlation of Aiyoshizawa or the new correlation of this study at the corresponding vapour quality point.

A plot may then be drawn from the lookup table created in EES which provides a visual means of comparing the calculated results to the experimental values of Dang. The results obtained in EES for each of the 28 data sets of Dang was exported to Microsoft Excel and equations (3.36) to (3.40) were used to perform a statistical analysis on the results.

EES Calculations Code - Aiyoshizawa Correlation:

```
/////////////////////////////////////////////////////////////////
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/////////////////////////////////////////////////////////////////
```

"ASSUMPTIONS:"

- "1. Pressure drops in the system are to be neglected."
- "2. CO2 enters the evaporator test section as a saturated liquid. (Quality x=0)"
- "3. CO2 leaves the evaporator test section as a saturated gas. (Quality x=1)"
- "4. Calculations are done at a constant mass flux."
- "5. The heat flux throughout the calculation is also constant."
- "6. The calculation is for a horizontal smooth tube, fixed inner diameter setup."
- "7. The saturation temperature, T_sat, is also specified as a constant input to the simulation."

```
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```
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"FUNCTIONS AND PROCEDURES SECTION:"
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```

"PROCEDURE - AIYOSHIZAWA"

Procedure AIYOSHIZAWA

(x,OCR,MassFlux,HeatFlux,D,mu,mu_l,mu_g,nu,g,h_lg,rho,rho_l,rho_g,sigma,cp,cp_l,lambda,lambda_l,T_sat:h_tp)

$$\text{CHI_tt} = ((1-x)/(x))^{0.9} \cdot ((\rho_g)/(\rho_l))^{0.5} \cdot ((\mu_l)/(\mu_g))^{0.1}$$
$$F = 0.8 + 0.5 \cdot (1/\text{CHI_tt})^{1.2}$$

$$\text{Re_tp} = ((\text{MassFlux} \cdot (1-x) \cdot D)/(\mu_l)) \cdot F^{1.25}$$

$$S = 1/(6 + (\text{Re_tp} \cdot 10^{-4})^3)$$

$$D_b = 0.51 \cdot ((2 \cdot \sigma)/(g \cdot (\rho_l - \rho_g)))^{0.5}$$

$$\text{Pr}_l = (\mu_l \cdot \text{cp}_l)/(\lambda_l)$$

$$h_{nb} =$$

$$(207)^{((\lambda_l)/(D_b)) \cdot ((\text{HeatFlux} \cdot D_b)/(\lambda_l \cdot T_{\text{sat}}))^{0.745} \cdot ((\rho_g)/(\rho_l))^{0.581} \cdot \text{Pr}_l^{0.533}}$$

$$\text{Pr} = (\mu \cdot \text{cp})/(\lambda)$$

$$h_{cb} = 0.023 \cdot ((\lambda_l)/(D)) \cdot ((\text{MassFlux} \cdot (1-x) \cdot D)/(\mu_l))^{0.8} \cdot \text{Pr}^{0.4}$$

$$h_{tp} = F \cdot h_{cb} + S \cdot h_{nb}$$

END


```

/////////////////////////////////////////////////////////////////
/////////////////////////////////////////////////////////////////
"MAIN PROGRAM SECTION:"
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/////////////////////////////////////////////////////////////////

/////////////////////////////////////////////////////////////////
"INPUT PARAMETERS:"
/////////////////////////////////////////////////////////////////

"Oil Concentration Ratio:"
OCR = 1

"CO2 Inlet Properties:"
x_i = 0
T_sat = 15+273.15
MassFlux = 720
HeatFlux = 18

"CO2 Outlet Properties:"
x_e = 1

"Pipe Geometry:"
D = 4/1000
L = 2

"Gravitational Constant:"
g = 9.8

"Number of Increments:"
N = 100

"Thermodynamic Properties:"
h = Enthalpy(R744,T=T_sat,x=0)
P = Pressure(R744,T=T_sat,x=0)
mu_l = Viscosity(R744,T=T_sat,x=0)
mu_g = Viscosity(R744,T=T_sat,x=1)
cp_l = Cp(R744,T=T_sat,x=0)
cp_g = Cp(R744,T=T_sat,x=1)
rho_l = Density(R744,T=T_sat,x=0)
rho_g = Density(R744,T=T_sat,x=1)
lambda_l = Conductivity(R744,T=T_sat,x=0)/1000[W/kW]
lambda_g = Conductivity(R744,T=T_sat,x=1)/1000[W/kW]
h_l = Enthalpy(R744,T=T_sat,x=0)
h_g = Enthalpy(R744,T=T_sat,x=1)
h_lg = h_g - h_l
sigma = SurfaceTension(R744,T=T_sat)

"Pipe Geometry Calculations:"
A_wall = PI*D*L
A_flow = PI*(D/2)^2

"Heat Transfer Calculations:"
Q_total = HeatFlux*A_wall
Q_inc = Q_total/N

"Mass Flow Rate Calculations:"
m_dot = MassFlux*A_flow

```

```

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
"SOLUTION LOOP:"
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////

```

"Loop Initilization:"

```

x_inc = (x_e-x_i)/N
x[0] = x_i
h[0] = h

```

DUPLICATE i = 1,N

```

x[i] = x[i-1] + x_inc
x_avg[i] = AverageQuality(x[i-1],x[i])

h_avg[i] = Average(h[i],h[i-1])

mu[i] = tpDynamicViscosity(x_avg[i],mu_l,mu_g,P,h_avg[i])
rho[i] = tpDensity(x_avg[i],rho_l,rho_g,P,h_avg[i])
nu[i] = mu[i]/rho[i]
cp[i] = tpSpecificHeat(x_avg[i],cp_l,cp_g,P,h_avg[i])
lambda[i] = tpConductivity(x_avg[i],lambda_l,lambda_g,P,h_avg[i])

V[i] = MassFlux/rho[i]
T_B[i] = T_sat

```

```

Call AIYOSHIKAWA
(x_avg[i],OCR,MassFlux,HeatFlux,D,mu[i],mu_l,mu_g,nu[i],g,h_lg,rho[i],rho_l,rho_g,sigma,cp[i],cp_l,lamb
da[i],lambda_l,T_sat:h_tp[i])

```

"Conservation of Energy:"

```

Q_inc = m_dot*(h[i] - h[i-1])

```

END

```

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```

"Store the quality and the h_tp in a lookup table:"

```

$CopyToLookup 'Predicted Data', 'Quality', 1, x_avg[1..N]
$CopyToLookup 'Predicted Data', 'HTC_pred', 1, h_tp[1..N]

```

"Number of rows in the experimental data lookup table."

```

K = NLOOKUPROWS('Experimental Data')

```

DUPLICATE i = 1,K

"h_tp assignment to experimental quality values:"

```

x_exp[i] = Lookup('Experimental Data', i, 'Quality')

HTC_pred[i] = INTERPOLATE2('Predicted Data','Quality', 'HTC_pred', Quality = x_exp[i])
HTC_exp[i] = Lookup('Experimental Data', i, 'HTC_exp')

```

END

```

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
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```

EES Calculations Code - New Correlation:

```
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```

"ASSUMPTIONS:"

"1. Pressure drops in the system are to be neglected."
"2. CO2 enters the evaporator test section as a saturated liquid. (Quality x=0)"
"3. CO2 leaves the evaporator test section as a saturated gas. (Quality x=1)"
"4. Calculations are done at a constant mass flux."
"5. The heat flux throughout the calculation is also constant."
"6. The calculation is for a horizontal smooth tube, fixed inner diameter setup."
"7. The saturation temperature, T_{sat}, is also specified as a constant input to the simulation."

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```

"FUNCTIONS AND PROCEDURES SECTION:"

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```

"PROCEDURE - newCORRELATION"

Procedure newCORRELATION

(S,x,x_dry,OCR,MassFlux,HeatFlux,D,mu,mu_l,mu_g,nu,g,h_lg,rho,rho_l,rho_g,sigma,cp,cp_l,lambda,lambdambda_l,T_sat,Re,Bo:h_cb,h_nb,F,M)

$$\text{CHI_tt} = ((1-x)/(x))^{0.9} \cdot ((\rho_g)/(\rho_l))^{0.5} \cdot ((\mu_l)/(\mu_g))^{0.1}$$
$$F = 0.8 + 0.5 \cdot (1/\text{CHI_tt})^{1.2}$$

$$D_b = 0.51 \cdot ((2 \cdot \sigma)/(g \cdot (\rho_l - \rho_g)))^{0.5}$$

$$\text{Pr}_l = (\mu_l \cdot \text{cp}_l)/(\lambda_{b_l})$$

$$h_{nb} =$$

$$(207)^* ((\lambda_{b_l})/(D_b)) \cdot ((\text{HeatFlux} \cdot D_b)/(\lambda_{b_l} \cdot T_{\text{sat}}))^{0.745} \cdot ((\rho_g)/(\rho_l))^{0.581} \cdot \text{Pr}_l^{0.533}$$

$$\text{Pr} = (\mu \cdot \text{cp})/(\lambda_{b_l})$$

$$h_{cb} = 0.023 \cdot ((\lambda_{b_l})/(D)) \cdot ((\text{MassFlux} \cdot (1-x) \cdot D)/(\mu_l))^{0.8} \cdot \text{Pr}^{0.4}$$

$$\text{ReBo} = \text{Re} \cdot \text{Bo}$$

If (x < x_dry) And (OCR > 0) Then

$$a = -0.0043 \cdot \text{ReBo} + 0.9535$$

$$b = 0.1851 \cdot \text{ReBo} - 0.0483$$

$$M = a + b \cdot x^2$$

Else

If (x > x_dry) And (OCR > 0) Then

$$x_{\text{corrected}} = x - x_{\text{dry}}$$

$$a = -19$$

$$b = -6.3 \cdot 10^{-5}$$

$$c = 2$$

$$k = 0.15$$

$$\text{slope} = a + b \cdot (\text{Re}) + c \cdot \ln(\text{Re}) + k$$

$$r = 0.79$$

$$s = -4.4$$

$$\text{intercept} = r + s/\ln(\text{Re})$$

```

    M = (slope*x_corrected+intercept)^(-1)
Else
    If (x < x_dry) And (OCR = 0) Then
        M = 1
    Else
        If (x > x_dry) And (OCR = 0) Then
            x_corrected = x-x_dry
            a = 200
            b = 0.2
            c = 0.5
            M = (EXP(-a*x_corrected^2)+b*x_corrected^c)^(-1)
        Endif
    Endif
Endif
Endif
Endif

END

"FUNCTION - PREDICTED DRYOUT QUALITY"

Function xDryout(MassFlux,D,mu_g,mu_l)

    D_ref = 0.002
    mu_avg = (mu_g+mu_l)/2
    Re_avg = (MassFlux*D)/mu_avg

    xDryout = 0.9549*EXP((-1)*(0.0000145)*(D_ref/D)^(3/2))*Re_avg)
End

"FUNCTION - SUPPRESSION FACTOR"

Function S(OCR,x,MassFlux,Re,Bo,Bd,D)

    D_ref = 0.002

    RefMassFlux = 720

    If OCR > 0 Then
        S_oil = 0.0087*OCR^2 - 0.065*OCR + (0.215*(0.675*((D/D_ref))^(0.38))*(MassFlux/RefMassFlux)^(-0.2))
    Else
        S_oil = 1
    Endif

    S = S_oil*(-0.206*LN(Re^1.65*Bo^0.2*Bd^0.053)+3.55*(D/D_ref)^0.0675)
END

"FUNCTION - AVERAGE QUALITY OF INCREMENT"

Function AverageQuality(x_i,x_e)

    If (x_i>=0) and (x_e<=1) Then
        AverageQuality = Average(x_i,x_e)
    Else
        AverageQuality = 100
    Endif

End

```

"FUNCTION - TWO-PHASE DENSITY OF FLUID"

```
Function tpDensity(x,rho_l,rho_g,P,h)

    If (x > 0) and (x < 1) Then
        tpDensity = (1-x)*rho_l + x*rho_g
    Else
        tpDensity = Density(R744,P=P,h=h)
    EndIf
End
```

"FUNCTION - TWO-PHASE DYNAMIC VISCOSITY"

```
Function tpDynamicViscosity(x,mu_l,mu_g,P,h)

    If (x > 0) and (x < 1) Then
        tpDynamicViscosity = (1-x)*mu_l + x*mu_g
    Else
        tpDynamicViscosity = Viscosity(R744,P=P,h=h)
    EndIf
End
```

"FUNCTION - TWO-PHASE SPECIFIC HEAT Cp"

```
Function tpSpecificHeat(x,cp_l,cp_g,P,h)

    If (x > 0) and (x < 1) Then
        tpSpecificHeat = (1-x)*cp_l + x*cp_g
    Else
        tpSpecificHeat = Cp(R744,P=P,h=h)
    EndIf
End
```

"FUNCTION - TWO-PHASE CONDUCTIVITY"

```
Function tpConductivity(x,lambda_l,lambda_g,P,h)

    If (x > 0) and (x < 1) Then
        tpConductivity = (1-x)*lambda_l + x*lambda_g
    Else
        tpConductivity = Conductivity(R744,P=P,h=h)/1000[W/kW]
    EndIf
End
```

```
////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////
"MAIN PROGRAM SECTION:"
////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////
```

```
////////////////////////////////////////////////////////////////
"INPUT PARAMETERS:"
////////////////////////////////////////////////////////////////
```

```
"Oil Concentration Ratio:"
OCR = 1
```

```
"CO2 Inlet Properties:"
x_i = 0
T_sat = 15+273.15
MassFlux = 360
HeatFlux = 18
```

"CO2 Outlet Properties:"

$x_e = 1$

"Pipe Geometry:"

$D = 2/1000$

$L = 2$

"Gravitational Constant:"

$g = 9.81$

"Number of Increments:"

$N = 100$

"Thermodynamic Properties:"

$h = \text{Enthalpy}(R744, T=T_{\text{sat}}, x=0)$

$P = \text{Pressure}(R744, T=T_{\text{sat}}, x=0)$

$\mu_l = \text{Viscosity}(R744, T=T_{\text{sat}}, x=0)$

$\mu_g = \text{Viscosity}(R744, T=T_{\text{sat}}, x=1)$

$cp_l = \text{Cp}(R744, T=T_{\text{sat}}, x=0)$

$cp_g = \text{Cp}(R744, T=T_{\text{sat}}, x=1)$

$\rho_l = \text{Density}(R744, T=T_{\text{sat}}, x=0)$

$\rho_g = \text{Density}(R744, T=T_{\text{sat}}, x=1)$

$\lambda_l = \text{Conductivity}(R744, T=T_{\text{sat}}, x=0)/1000[\text{W/kW}]$

$\lambda_g = \text{Conductivity}(R744, T=T_{\text{sat}}, x=1)/1000[\text{W/kW}]$

$h_l = \text{Enthalpy}(R744, T=T_{\text{sat}}, x=0)$

$h_g = \text{Enthalpy}(R744, T=T_{\text{sat}}, x=1)$

$h_{lg} = h_g - h_l$

$\sigma = \text{SurfaceTension}(R744, T=T_{\text{sat}})$

"Pipe Geometry Calculations:"

$A_{\text{wall}} = \pi D L$

$A_{\text{flow}} = \pi (D/2)^2$

"Heat Transfer Calculations:"

$Q_{\text{total}} = \text{HeatFlux} * A_{\text{wall}}$

$Q_{\text{inc}} = Q_{\text{total}}/N$

"Mass Flow Rate Calculations:"

$\dot{m} = \text{MassFlux} * A_{\text{flow}}$

"Predicted Dryout Quality:"

$x_{\text{dry}} = \text{xDryout}(\text{MassFlux}, D, \mu_g, \mu_l)$

$x_{\text{dry}}[0] = x_{\text{dry}}$

$x_{\text{dry}}[1] = x_{\text{dry}}$

$x_{\text{dry_plot}}[0] = 0$

$x_{\text{dry_plot}}[1] = 100$

"Dimensionless Numbers:"

$Re = ((\text{MassFlux} * D) / (\mu_l))$

$Bo = \text{HeatFlux} / (\text{MassFlux} * h_{lg})$

$Bd = g * \rho_l * D^2 / \sigma$

///
"SOLUTION LOOP:"
///

"Loop Initialization:"

$x_{\text{inc}} = (x_e - x_i) / N$

$x[0] = x_i$

$h[0] = h$

DUPLICATE i = 1,N

```
x[i] = x[i-1] + x_inc
x_avg[i] = AverageQuality(x[i-1],x[i])
h_avg[i] = Average(h[i],h[i-1])
mu[i] = tpDynamicViscosity(x_avg[i],mu_l,mu_g,P,h_avg[i])
rho[i] = tpDensity(x_avg[i],rho_l,rho_g,P,h_avg[i])
nu[i] = mu[i]/rho[i]
cp[i] = tpSpecificHeat(x_avg[i],cp_l,cp_g,P,h_avg[i])
lambda[i] = tpConductivity(x_avg[i],lambda_l,lambda_g,P,h_avg[i])
```

```
V[i] = MassFlux/rho[i]
T_B[i] = T_sat
```

```
S[i] = S(OCR,x_avg[i],MassFlux,Re,Bo,Bd,D)
```

```
Call newCORRELATION
(S[i],x_avg[i],x_dry,OCR,MassFlux,HeatFlux,D,mu[i],mu_l,mu_g,nu[i],g,h_lg,rho[i],rho_l,rho_g,sigma,cp[i],
cp_l,lambda[i],lambda_l,T_sat,Re,Bo:h_cb[i],h_nb[i],F[i], M[i])
```

```
h_tp[i] = (F[i]*h_cb[i] + S[i]*h_nb[i])*(1/M[i])
```

```
"Conservation of Energy:"
Q_inc = m_dot*(h[i] - h[i-1])
```

END

```
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
```

```
"Store the quality and the h_tp in a lookup table:"
```

```
$CopyToLookup 'Predicted Data', 'Quality', 1, x_avg[1..N]
$CopyToLookup 'Predicted Data', 'HTC_pred', 1, h_tp[1..N]
```

```
"Number of rows in the experimental data lookup table."
```

```
K = NLOOKUPROWS('Experimental Data')
```

DUPLICATE i = 1,K

```
"h_tp assignment to experimental quality values:"
x_exp[i] = Lookup('Experimental Data', i, 'Quality')
```

```
HTC_pred[i] = INTERPOLATE2('Predicted Data','Quality', 'HTC_pred', Quality = x_exp[i])
HTC_exp[i] = Lookup('Experimental Data', i, 'HTC_exp')
```

END

```
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
```

APPENDIX B: HTC DATA SETS

This section contains data sets for different combinations of input parameters. The input parameters correspond to the experimental values considered in the study by Dang et al. (2013). The experimental results from the study by Dang et al. (2013) for the convection heat transfer coefficient at a specific vapour quality point is given for each data set along with the calculation results by the correlation of Aiyoshizawa et al. (2006) and the new correlation of this study. Following the data sets, graphical representations of the data sets are also given in order to demonstrate how each of the correlation predictions fit the experimental results.

Convection heat transfer coefficient data sets:

Data Set 01:				0.3992	7.55	8.346	7.95	0.7469	9.10	9.743	8.859
Input Parameters:				0.4018	8.08	8.354	7.955	0.7882	10.56	10	8.021
HeatFlux:	9	kWm-2		0.4098	8.27	8.378	7.968	0.7895	12.51	10.01	7.919
MassFlux:	360	kgm-2s-1		0.4098	8.82	8.378	7.968	0.7908	11.31	10.02	7.814
T_sat:	15	C		0.4258	8.15	8.427	7.996	0.8002	12.31	10.08	6.959
Diameter:	2	mm		0.4351	8.27	8.457	8.012	0.8002	11.45	10.08	6.959
OCR's:				0.4431	8.62	8.482	8.027	0.8055	10.43	10.12	6.424
OCR_exp:	0	%		0.4511	8.66	8.508	8.041	0.8162	8.66	10.2	5.323
Data:				0.4658	7.87	8.555	8.069	0.8268	12.82	10.29	4.27
Quality	HTC_Dang	HTC_Aiyo	HTC_new	0.4671	7.52	8.56	8.071	0.8308	11.68	10.32	3.902
0.1061	8.48	7.592	7.583	0.4711	8.43	8.573	8.079	0.8575	8.03	10.56	2.007
0.1074	8.89	7.595	7.584	0.4844	8.96	8.617	8.105	0.8681	1.40	10.67	1.553
0.1141	8.71	7.610	7.59	0.4898	8.01	8.635	8.116	0.8721	7.29	10.71	1.421
0.1794	7.83	7.758	7.654	0.5031	7.25	8.681	8.143	0.8788	1.81	10.79	1.241
0.1847	8.31	7.770	7.66	0.5031	8.50	8.681	8.143	0.8801	1.28	10.8	1.212
0.1860	9.13	7.773	7.661	0.5124	9.80	8.713	8.163	0.9187	1.00	11.36	0.88
0.1887	7.94	7.780	7.664	0.5164	7.36	8.727	8.171	0.9414	0.82	11.85	0.9245
0.2233	8.08	7.864	7.703	0.5337	7.76	8.789	8.209	0.9774	0.63	13.5	1.146
0.2246	8.43	7.867	7.705	0.5351	7.94	8.794	8.212	Data Set 02:			
0.2246	8.20	7.867	7.705	0.5404	8.64	8.813	8.224	Input Parameters:			
0.2540	8.24	7.941	7.74	0.5630	9.15	8.897	8.276	HeatFlux:	18	kWm-2	
0.2540	8.45	7.941	7.74	0.5630	8.34	8.897	8.276	MassFlux:	720	kgm-2s-1	
0.2593	8.94	7.955	7.747	0.5777	8.66	8.954	8.312	T_sat:	15	C	
0.2593	9.06	7.955	7.747	0.5777	7.45	8.954	8.312	Diameter:	4	mm	
0.2593	9.40	7.955	7.747	0.5857	9.71	8.985	8.332	OCR's:			
0.2659	7.78	7.972	7.755	0.5897	7.64	9.001	8.342	OCR_exp:	0	%	
0.2659	7.78	7.972	7.755	0.6043	8.08	9.059	8.38	Data:			
0.2819	7.80	8.014	7.776	0.6097	8.27	9.082	8.395	Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.2913	7.48	8.039	7.789	0.6376	9.45	9.199	8.473	0.0889	9.31	7.556	8.49
0.2939	7.87	8.046	7.792	0.6403	8.36	9.211	8.481	0.0898	9.17	7.558	8.491
0.3019	7.69	8.068	7.803	0.6443	7.52	9.229	8.493	0.0963	9.39	7.572	8.5
0.3219	8.29	8.122	7.831	0.6510	8.03	9.258	8.513	0.1874	9.24	7.777	8.633
0.3232	8.43	8.126	7.833	0.6603	11.08	9.3	8.542	0.1874	9.39	7.777	8.633
0.3352	8.82	8.159	7.85	0.6643	7.85	9.319	8.554	0.1948	9.49	7.794	8.645
0.3379	8.24	8.167	7.854	0.6776	8.01	9.381	8.597	0.2804	9.65	8.010	8.802
0.3379	9.20	8.167	7.854	0.6789	7.73	9.387	8.602	0.2849	9.45	8.022	8.811
0.3605	8.75	8.231	7.888	0.7136	7.92	9.56	8.725	0.2933	9.67	8.044	8.828
0.3645	8.01	8.243	7.894	0.7149	8.99	9.567	8.73	0.3742	9.64	8.271	9.007
0.3645	7.66	8.243	7.894	0.7242	8.03	9.616	8.766	0.3788	9.50	8.285	9.018
0.3739	8.03	8.27	7.909	0.7282	10.12	9.638	8.782				
0.3925	7.43	8.326	7.939	0.7389	7.97	9.697	8.825				
				0.7455	9.94	9.735	8.853				
				0.7455	12.17	9.735	8.853				

0.3862	9.72	8.307	9.036
0.4746	9.56	8.584	9.274
0.4773	9.45	8.593	9.282
0.4829	9.67	8.612	9.299
0.5665	8.61	8.911	9.575
0.5720	8.75	8.932	9.596
0.5748	8.86	8.943	9.606
0.6668	8.58	9.33	9.996
0.6696	8.37	9.343	10.01
0.6715	8.78	9.352	10.02
0.7606	7.37	9.824	4.585
0.7661	7.06	9.857	4.027
0.7688	6.95	9.874	3.773
0.8567	2.06	10.55	0.9773
0.8650	2.04	10.64	0.9893
0.8659	1.91	10.64	0.9911
0.9459	1.63	11.97	1.351
0.9496	1.65	12.09	1.377
0.9579	1.67	12.38	1.443

Data Set 03:

Input Parameters:

HeatFlux:	18	kWm-2
MassFlux:	720	kgm-2s-1
T_sat:	15	C
Diameter:	6	mm

OCR's:

OCR_exp:	0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0377	7.24	7.019	7.673
0.0423	7.16	7.022	7.677
0.0482	7.59	7.026	7.682
0.0488	7.77	7.026	7.683
0.0877	7.50	7.072	7.723
0.0923	7.46	7.079	7.729
0.0969	7.69	7.087	7.734
0.1331	7.22	7.165	7.779
0.1430	8.09	7.191	7.792
0.1436	7.84	7.193	7.793
0.1443	7.97	7.194	7.794
0.1811	7.67	7.309	7.846
0.1811	7.71	7.309	7.846
0.1897	8.00	7.339	7.859
0.1917	8.14	7.346	7.862
0.2292	7.58	7.498	7.922
0.2358	8.19	7.528	7.933
0.2371	8.06	7.533	7.935
0.2766	7.05	7.729	8.005
0.2766	6.94	7.729	8.005
0.2785	7.55	7.74	8.008
0.2792	7.44	7.743	8.01
0.3233	6.73	8.001	8.094
0.3233	6.64	8.001	8.094
0.3279	7.32	8.03	8.103
0.3279	7.25	8.03	8.103
0.3687	6.65	8.307	8.189
0.3740	7.11	8.346	8.201

0.3740	7.22	8.346	8.201
0.4108	6.55	8.629	8.285
0.4148	6.55	8.662	8.295
0.4200	7.01	8.704	8.307
0.4207	7.06	8.71	8.309
0.4543	6.77	9.001	8.394
0.4635	7.29	9.085	8.418
0.4654	6.83	9.102	8.423
0.4681	7.39	9.127	8.43
0.5517	6.74	9.985	8.676
0.5563	6.82	10.04	8.691
0.5569	7.21	10.04	8.693
0.5582	7.11	10.06	8.698
0.6451	6.94	11.14	9.019
0.6471	7.12	11.17	9.028
0.6471	7.47	11.17	9.028
0.6537	7.63	11.26	9.056
0.7333	5.38	12.48	9.502
0.7399	5.19	12.59	9.523
0.7412	4.74	12.61	9.515
0.7419	4.84	12.62	9.509
0.8261	2.60	14.23	2.434
0.8274	2.53	14.26	2.354
0.8347	2.41	14.42	1.962
0.8366	2.51	14.46	1.873
0.8715	1.97	15.31	1.022
0.8722	1.88	15.33	1.016
0.9176	1.52	16.73	0.9919
0.9261	1.53	17.05	1.026

Data Set 04:

Input Parameters:

HeatFlux:	4.5	kWm-2
MassFlux:	360	kgm-2s-1
T_sat:	15	C
Diameter:	2	mm

OCR's:

OCR_exp:	0	%
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Data:

Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0784	5.41	5.287	5.428
0.0789	5.52	5.288	5.428
0.0815	5.43	5.292	5.43
0.1147	5.44	5.345	5.458
0.1147	5.37	5.345	5.458
0.1333	5.04	5.377	5.475
0.1350	5.34	5.380	5.477
0.1350	5.21	5.380	5.477
0.1532	5.97	5.411	5.494
0.1549	5.22	5.414	5.496
0.1571	5.26	5.418	5.498
0.1717	5.15	5.444	5.513
0.1730	5.09	5.447	5.514
0.1903	6.23	5.479	5.533
0.1903	6.31	5.479	5.533
0.1943	4.83	5.486	5.537
0.1947	5.13	5.487	5.538
0.2089	5.43	5.514	5.554

0.2102	5.72	5.516	5.555
0.2142	5.18	5.524	5.56
0.2248	5.06	5.545	5.572
0.2305	5.93	5.556	5.579
0.2314	5.67	5.557	5.58
0.2336	5.54	5.562	5.582
0.2372	5.41	5.569	5.587
0.2442	5.20	5.583	5.595
0.2447	6.01	5.584	5.596
0.2495	5.86	5.594	5.602
0.2557	5.46	5.606	5.61
0.2566	5.62	5.608	5.611
0.2575	5.24	5.61	5.612
0.2610	5.10	5.617	5.616
0.2632	4.94	5.622	5.619
0.2668	5.82	5.629	5.624
0.2690	6.01	5.634	5.626
0.2703	6.28	5.636	5.628
0.2725	5.11	5.641	5.631
0.2739	5.65	5.644	5.633
0.2823	5.42	5.661	5.644
0.2836	6.10	5.664	5.645
0.2853	5.01	5.668	5.648
0.2858	5.09	5.669	5.648
0.2920	5.92	5.682	5.657
0.2937	5.47	5.686	5.659
0.2982	5.20	5.695	5.665
0.2991	5.36	5.697	5.666
0.2995	5.92	5.698	5.667
0.2995	5.77	5.698	5.667
0.3030	5.53	5.706	5.672
0.3039	5.88	5.708	5.673
0.3097	5.12	5.72	5.681
0.3114	5.38	5.724	5.683
0.3172	5.10	5.737	5.692
0.3176	5.26	5.738	5.692
0.3189	4.95	5.741	5.694
0.3282	5.24	5.761	5.707
0.3309	5.04	5.768	5.711
0.3349	5.19	5.777	5.717
0.3433	5.62	5.796	5.729
0.3477	5.29	5.806	5.736
0.3508	5.16	5.813	5.741
0.3530	5.42	5.818	5.744
0.3530	6.23	5.818	5.744
0.3583	5.91	5.83	5.752
0.3601	5.71	5.835	5.755
0.3654	5.46	5.847	5.763
0.3747	6.16	5.869	5.778
0.3760	6.38	5.872	5.78
0.3773	5.87	5.875	5.782
0.3870	5.50	5.899	5.797
0.3897	5.79	5.905	5.802
0.3923	5.61	5.912	5.806
0.3963	5.56	5.922	5.813
0.3963	5.91	5.922	5.813
0.4025	5.78	5.937	5.823
0.4100	5.28	5.956	5.836
0.4105	5.42	5.957	5.837
0.4122	5.11	5.961	5.839
0.4122	4.96	5.961	5.839

0.4140	5.71	5.966	5.843
0.4149	6.00	5.968	5.844
0.4237	5.56	5.99	5.859
0.4304	5.43	6.008	5.871
0.4330	5.73	6.014	5.876
0.4374	5.85	6.026	5.884
0.4379	5.60	6.027	5.885
0.4436	5.74	6.042	5.895
0.4449	5.32	6.046	5.897
0.4480	5.23	6.054	5.903
0.4494	5.51	6.058	5.905
0.4511	5.83	6.062	5.909
0.4573	5.208	6.079	5.92
0.4604	5.328	6.087	5.926
0.4622	4.726	6.092	5.929
0.4653	5.439	6.1	5.935
0.4666	4.776	6.104	5.938
0.4697	5.529	6.112	5.944
0.4706	4.977	6.115	5.945
0.4737	5.128	6.123	5.951
0.4799	5.198	6.141	5.964
0.4847	5.158	6.154	5.973
0.4861	5.51	6.158	5.976
0.4909	5.63	6.172	5.985
0.4923	4.907	6.176	5.988
0.4949	4.726	6.183	5.994
0.5055	4.797	6.214	6.015
0.5298	5.531	6.286	6.067
0.5382	5.611	6.311	6.086
0.5475	5.34	6.34	6.107
0.5564	5.511	6.368	6.128
0.5568	5.652	6.37	6.129
0.5572	5.752	6.371	6.13
0.563	5.471	6.389	6.143
0.5696	5.18	6.411	6.159
0.5838	5.602	6.458	6.194
0.5851	5.271	6.462	6.198
0.6015	5.422	6.518	6.24
0.6107	5.412	6.551	6.265
0.6209	5.412	6.587	6.293
0.6284	5.714	6.615	6.314
0.6302	5.402	6.621	6.319
0.6302	5.181	6.621	6.319
0.6324	4.89	6.629	6.325
0.6483	5.242	6.69	6.372
0.6563	5.664	6.721	6.396
0.6576	5.252	6.726	6.4
0.6576	5.574	6.726	6.4
0.6731	5.695	6.789	6.45
0.6899	5.153	6.86	6.506
0.6925	4.962	6.871	6.515
0.6956	4.691	6.884	6.526
0.6974	5.364	6.892	6.533
0.6987	4.811	6.898	6.537
0.704	5.063	6.922	6.556
0.708	5.173	6.94	6.571
0.7115	4.892	6.956	6.584
0.7275	4.973	7.032	6.646
0.7279	5.194	7.034	6.648
0.7571	5.004	7.183	6.78
0.7611	4.913	7.205	6.82

0.7677	4.974	7.241	6.854
0.7717	5.084	7.264	6.796
0.7752	5.124	7.284	6.712
0.7774	6.963	7.297	6.642
0.7823	8.138	7.326	6.442
0.788	4.753	7.361	6.143
0.7982	5.004	7.425	5.476
0.8008	8.138	7.442	5.288
0.826	7.165	7.618	3.347
0.8336	7.828	7.677	2.818
0.8362	8.631	7.697	2.648
0.8415	9.395	7.74	2.328
0.8433	7.908	7.755	2.226
0.8623	7.999	7.925	1.384
0.8685	8.351	7.986	1.197
0.8747	9.094	8.051	1.049
0.8787	7.196	8.094	0.9705
0.8972	4.977	8.317	0.7552
0.9056	1.863	8.434	0.7152
0.91	4.224	8.501	0.7033
0.9162	1.703	8.6	0.697
0.9361	1.311	8.992	0.724
0.9432	1.05	9.169	0.7461

Data Set 05:

Input Parameters:			
HeatFlux:	9	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1161	8.77	7.614	7.592
0.1167	8.26	7.615	7.592
0.1225	8.48	7.628	7.598
0.1906	8.18	7.784	7.666
0.1906	7.68	7.784	7.666
0.1912	8.94	7.786	7.667
0.2288	7.90	7.878	7.709
0.2332	8.00	7.889	7.715
0.2377	8.19	7.900	7.72
0.2600	8.15	7.957	7.748
0.2606	8.19	7.958	7.748
0.2689	9.19	7.980	7.759
0.2689	8.76	7.980	7.759
0.2734	7.57	7.992	7.765
0.2912	7.60	8.039	7.788
0.3020	7.22	8.068	7.803
0.3058	7.47	8.078	7.808
0.3071	7.54	8.082	7.81
0.3319	8.14	8.15	7.845
0.3338	8.12	8.155	7.848
0.3440	8.64	8.184	7.863
0.3440	8.96	8.184	7.863
0.3447	8.03	8.186	7.864
0.3657	8.51	8.246	7.896

0.3695	7.49	8.258	7.902
0.3784	7.83	8.284	7.916
0.3784	7.90	8.284	7.916
0.4032	7.33	8.358	7.957
0.4032	7.37	8.358	7.957
0.4115	7.86	8.383	7.971
0.4172	8.47	8.401	7.981
0.4223	8.11	8.416	7.99
0.4389	7.98	8.469	8.019
0.4421	8.07	8.479	8.025
0.4503	8.28	8.505	8.04
0.4529	8.40	8.513	8.045
0.4720	7.60	8.576	8.081
0.4720	7.41	8.576	8.081
0.4784	8.20	8.597	8.093
0.4962	7.85	8.657	8.129
0.4968	8.91	8.659	8.13
0.5070	8.27	8.694	8.151
0.5095	7.00	8.703	8.156
0.5191	9.67	8.737	8.177
0.5236	7.16	8.753	8.187
0.5433	7.55	8.824	8.23
0.5433	7.78	8.824	8.23
0.5477	8.56	8.84	8.24
0.5700	8.20	8.924	8.293
0.5713	8.96	8.929	8.296
0.5828	8.46	8.974	8.325
0.5828	7.29	8.974	8.325
0.5929	9.49	9.014	8.35
0.5974	7.32	9.032	8.362
0.6120	7.92	9.091	8.401
0.6159	8.05	9.107	8.411
0.6432	9.30	9.224	8.489
0.6490	8.21	9.249	8.507
0.6528	7.39	9.266	8.518
0.6560	7.88	9.281	8.528
0.6617	10.86	9.307	8.546
0.6700	7.67	9.345	8.573
0.6808	7.56	9.396	8.608
0.6853	7.85	9.418	8.623
0.7177	8.78	9.581	8.74
0.7215	7.78	9.602	8.755
0.7260	7.78	9.626	8.773
0.7362	9.91	9.682	8.814
0.7413	7.80	9.711	8.835
0.7502	12.02	9.762	8.874
0.7540	8.97	9.784	8.891
0.7547	9.84	9.788	8.894
0.7903	10.46	10.01	7.855
0.7954	12.34	10.05	7.407
0.7973	11.18	10.06	7.234
0.8005	12.21	10.09	6.93
0.8056	11.31	10.12	6.414
0.8151	10.23	10.19	5.434
0.8190	8.44	10.22	5.04
0.8330	12.66	10.34	3.705
0.8381	11.52	10.38	3.276
0.8654	7.81	10.64	1.655
0.8743	1.15	10.74	1.357
0.8794	7.09	10.79	1.228
0.8845	1.55	10.85	1.126

0.8871	1.12	10.89	1.082
0.9202	0.74	11.39	0.8798
0.9431	0.64	11.9	0.9309
0.9807	0.51	13.82	1.184

Data Set 06:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1623	11.42	11.560	11.07
0.1628	11.79	11.560	11.07
0.1676	11.25	11.570	11.07
0.1978	11.01	11.670	11.11
0.2015	11.43	11.680	11.11
0.2021	11.86	11.690	11.11
0.2021	10.94	11.690	11.11
0.2227	11.89	11.750	11.14
0.2265	11.32	11.770	11.14
0.2265	11.72	11.770	11.14
0.2270	11.48	11.770	11.14
0.2344	11.26	11.790	11.15
0.2344	12.48	11.790	11.15
0.2413	11.62	11.820	11.16
0.2535	11.98	11.86	11.17
0.2572	11.55	11.87	11.18
0.2631	11.71	11.89	11.18
0.2636	11.62	11.89	11.19
0.2647	10.82	11.9	11.19
0.2689	12.94	11.91	11.19
0.2721	11.84	11.92	11.2
0.2795	11.64	11.95	11.21
0.2822	11.96	11.96	11.21
0.2838	11.29	11.97	11.21
0.2912	10.93	11.99	11.22
0.2986	11.42	12.02	11.23
0.3007	11.78	12.03	11.23
0.3018	11.58	12.03	11.24
0.3018	11.67	12.03	11.24
0.3060	12.72	12.04	11.24
0.3135	11.30	12.07	11.25
0.3299	12.14	12.13	11.28
0.3342	12.48	12.15	11.28
0.3363	12.03	12.16	11.29
0.3421	11.37	12.18	11.29
0.3437	11.52	12.18	11.3
0.3453	12.77	12.19	11.3
0.3479	11.91	12.2	11.3
0.3527	11.90	12.22	11.31
0.3644	11.92	12.26	11.33
0.3665	11.99	12.27	11.33
0.3670	11.72	12.27	11.33
0.3697	12.10	12.28	11.34

0.3718	11.55	12.29	11.34
0.3750	11.71	12.3	11.34
0.3819	11.43	12.33	11.36
0.3824	12.95	12.33	11.36
0.3915	11.45	12.37	11.37
0.4042	11.55	12.42	11.39
0.4047	11.96	12.42	11.39
0.4047	11.37	12.42	11.39
0.4052	11.86	12.42	11.39
0.4084	11.61	12.43	11.4
0.4116	12.42	12.45	11.4
0.4132	11.66	12.45	11.41
0.4153	11.12	12.46	11.41
0.4212	11.70	12.48	11.42
0.4217	11.02	12.49	11.42
0.4243	11.74	12.5	11.43
0.4307	11.19	12.52	11.44
0.4365	11.47	12.55	11.45
0.4371	11.57	12.55	11.45
0.4371	11.81	12.55	11.45
0.4381	11.65	12.55	11.45
0.4450	11.02	12.58	11.46
0.4450	11.84	12.58	11.46
0.4456	12.56	12.58	11.46
0.4472	10.81	12.59	11.47
0.4503	11.53	12.6	11.47
0.4519	11.34	12.61	11.48
0.4519	11.29	12.61	11.48
0.4546	11.47	12.62	11.48
0.4588	11.62	12.64	11.49
0.4636	11.68	12.66	11.5
0.4673	11.71	12.67	11.51
0.4721	11.27	12.69	11.51
0.4742	11.77	12.7	11.52
0.4769	11.87	12.71	11.52
0.4774	11.50	12.72	11.52
0.4785	12.04	12.72	11.53
0.4832	11.38	12.74	11.54
0.4843	11.18	12.75	11.54
0.4854	11.66	12.75	11.54
0.4859	12.89	12.75	11.54
0.4875	11.72	12.76	11.54
0.4949	12.46	12.79	11.56
0.5045	11.18	12.83	11.58
0.5108	11.29	12.86	11.59
0.5151	11.07	12.88	11.6
0.5172	11.59	12.89	11.61
0.5172	11.35	12.89	11.61
0.5182	11.69	12.89	11.61
0.5193	11.46	12.9	11.61
0.532	11.14	12.96	11.64
0.5336	11.27	12.96	11.64
0.5442	11.09	13.01	11.67
0.5442	10.98	13.01	11.67
0.5501	12.7	13.04	11.68
0.5527	12.53	13.05	11.69
0.5543	12.27	13.06	11.69
0.5559	11.82	13.07	11.69
0.5559	11.61	13.07	11.69
0.5564	13.05	13.07	11.69
0.5564	11.51	13.07	11.69

0.5607	12.56	13.09	11.7
0.5713	13.5	13.14	11.73
0.5771	12.04	13.17	11.74
0.5835	11.38	13.2	11.76
0.5851	11.67	13.21	11.76
0.6249	11.78	13.41	11.87
0.6249	12.37	13.41	11.87
0.6254	13.67	13.41	11.87
0.6259	12.14	13.41	11.87
0.6265	12.62	13.42	11.87
0.6275	11.95	13.42	11.88
0.6297	12.78	13.43	11.88
0.6445	12.45	13.51	11.93
0.6477	11.62	13.53	11.94
0.6541	12.86	13.56	11.96
0.6546	14.21	13.57	11.96
0.6933	14.22	13.79	12.08
0.6944	13.74	13.79	12.09
0.6954	13.65	13.8	12.09
0.6986	12.32	13.82	12.1
0.7008	13.04	13.83	12.11
0.7008	13.13	13.83	12.11
0.714	12.63	13.91	12.16
0.7161	12.51	13.92	12.17
0.7321	14.59	14.03	12.23
0.7342	14.03	14.04	12.24
0.7636	12.23	14.24	12.46
0.7676	12.86	14.27	12.45
0.7713	11.12	14.29	12.34
0.7724	10.62	14.3	12.3
0.7729	14.53	14.31	12.28
0.7771	13	14.34	12.04
0.7867	9.707	14.41	11.22
0.7909	11.5	14.44	10.76
0.8008	11.06	14.52	9.497
0.8063	12.11	14.57	8.723
0.8329	5.899	14.8	5.081
0.8419	7.273	14.89	4.073
0.8424	5.67	14.89	4.021
0.8424	6.864	14.89	4.021
0.8424	5.55	14.89	4.021
0.8514	3.947	14.98	3.193
0.861	3.622	15.09	2.501
0.8642	3.321	15.12	2.313
0.8748	2.007	15.25	1.821
0.8801	2.778	15.31	1.64
0.913	1.417	15.81	1.185
0.9188	1.357	15.91	1.175
0.9331	1.213	16.22	1.193
0.939	1.189	16.36	1.212
0.9517	1.177	16.74	1.271

Data Set 07:

Input Parameters:			
HeatFlux:	36	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:			
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OCR_exp:	0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1251	15.37	17.820	16.55
0.1267	15.22	17.830	16.55
0.1283	15.97	17.830	16.55
0.1283	15.86	17.830	16.55
0.1288	15.44	17.840	16.55
0.1294	15.62	17.840	16.55
0.1304	14.40	17.840	16.56
0.1320	16.07	17.850	16.56
0.1983	15.72	18.160	16.62
0.1983	15.62	18.160	16.62
0.1989	15.82	18.160	16.63
0.2010	16.36	18.170	16.63
0.2021	15.90	18.180	16.63
0.2042	16.03	18.190	16.63
0.2047	16.14	18.19	16.63
0.2334	14.97	18.33	16.67
0.2424	15.26	18.37	16.68
0.2726	15.78	18.52	16.71
0.2742	16.23	18.53	16.72
0.2753	15.93	18.54	16.72
0.2753	16.08	18.54	16.72
0.2758	15.61	18.54	16.72
0.2811	15.53	18.57	16.73
0.3055	15.49	18.69	16.76
0.3119	16.23	18.72	16.77
0.3241	15.07	18.79	16.78
0.3257	15.64	18.79	16.79
0.3421	16.43	18.88	16.81
0.3479	16.40	18.91	16.82
0.3485	16.07	18.91	16.82
0.3495	16.17	18.92	16.82
0.3511	16.29	18.93	16.82
0.3787	15.21	19.07	16.87
0.3872	15.47	19.12	16.88
0.3968	15.42	19.17	16.9
0.3978	15.80	19.18	16.9
0.4174	15.68	19.29	16.93
0.4196	15.77	19.3	16.94
0.4217	16.45	19.31	16.94
0.4222	16.28	19.31	16.94
0.4238	16.05	19.32	16.94
0.4238	15.95	19.32	16.94
0.4243	16.51	19.32	16.94
0.4466	15.92	19.45	16.98
0.4546	15.97	19.5	17
0.4620	15.93	19.54	17.01
0.4716	15.81	19.59	17.03
0.4732	16.92	19.6	17.03
0.4891	15.76	19.7	17.07
0.4928	16.58	19.72	17.07
0.4938	16.50	19.72	17.07
0.4944	17.03	19.73	17.08
0.4960	17.19	19.74	17.08
0.4976	16.37	19.75	17.08
0.5013	16.21	19.77	17.09
0.5198	15.59	19.88	17.13
0.5342	15.61	19.97	17.16

0.5448	16.90	20.03	17.18
0.5480	15.86	20.05	17.19
0.5633	16.73	20.15	17.23
0.5644	16.83	20.15	17.23
0.5665	15.91	20.17	17.24
0.5681	17.04	20.18	17.24
0.5692	16.13	20.18	17.24
0.5697	16.44	20.19	17.24
0.5729	16.21	20.21	17.25
0.5973	16.36	20.37	17.31
0.6015	15.92	20.39	17.32
0.6191	16.57	20.51	17.37
0.6191	16.26	20.51	17.37
0.6323	15.90	20.6	17.41
0.6366	15.46	20.63	17.42
0.6371	16.25	20.63	17.42
0.6413	16.07	20.66	17.43
0.6413	15.90	20.66	17.43
0.6419	15.75	20.67	17.44
0.6435	16.30	20.68	17.44
0.6461	15.57	20.7	17.45
0.6657	15.95	20.84	17.51
0.6742	15.73	20.9	17.54
0.6928	16.59	21.04	17.6
0.6933	17.07	21.04	17.6
0.7076	15.38	21.15	17.65
0.7076	16.06	21.15	17.65
0.7130	13.60	21.19	17.67
0.7180	16.36	21.23	17.69
0.7180	15.80	21.23	17.69
0.7209	15.27	21.25	17.7
0.7408	15.20	21.41	17.78
0.7490	14.56	21.48	17.82
0.7618	13.44	21.59	17.97
0.7692	13.83	21.66	17.94
0.7809	13.83	21.76	16.98
0.7835	14.35	21.79	16.64
0.7862	11.39	21.81	16.25
0.7899	15.65	21.85	15.67
0.7899	15.6	21.85	15.67
0.7915	13.48	21.86	15.4
0.7962	14.47	21.91	14.55
0.8148	10.86	22.09	10.78
0.8238	9.274	22.19	8.965
0.8376	4.923	22.34	6.488
0.8408	4.778	22.37	5.989
0.8848	2.007	22.95	2.148
0.8949	1.598	23.1	1.875
0.9124	1.285	23.41	1.67
0.9167	1.273	23.5	1.655
0.9867	1.021	27.01	2.131
0.9867	0.985	27.01	2.131

Data Set 08:

Input Parameters:		
HeatFlux:	18	kWm-2
MassFlux:	1440	kgm-2s-1
T_sat:	15	C
Diameter:	2	mm

OCR's:		
OCR_exp:	0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0655	9.86	11.050	9.874
0.0716	9.37	11.090	9.888
0.0716	8.44	11.090	9.888
0.1033	10.21	11.280	9.966
0.1039	10.03	11.280	9.967
0.1088	9.61	11.310	9.98
0.1126	9.07	11.340	9.991
0.1406	10.36	11.520	10.07
0.1439	10.43	11.550	10.08
0.1439	9.82	11.550	10.08
0.1488	9.21	11.580	10.09
0.1685	10.27	11.720	10.15
0.1691	9.82	11.730	10.16
0.1767	8.97	11.780	10.18
0.1773	10.78	11.79	10.18
0.1778	9.30	11.79	10.18
0.1811	10.44	11.82	10.19
0.1822	10.87	11.82	10.2
0.1877	9.68	11.87	10.22
0.2047	9.71	12	10.27
0.2052	10.03	12	10.27
0.2162	9.77	12.09	10.31
0.2167	10.06	12.09	10.31
0.2189	9.48	12.11	10.32
0.2293	9.02	12.19	10.36
0.2392	9.76	12.28	10.39
0.2409	9.91	12.29	10.4
0.2518	10.60	12.38	10.44
0.2551	10.66	12.41	10.45
0.2551	10.04	12.41	10.45
0.2567	10.28	12.43	10.46
0.2578	9.86	12.43	10.46
0.2644	9.19	12.49	10.49
0.2770	10.49	12.6	10.54
0.2896	10.38	12.72	10.59
0.2902	12.24	12.72	10.59
0.2929	11.60	12.75	10.6
0.2940	12.48	12.76	10.61
0.3039	10.65	12.85	10.65
0.3170	9.74	12.97	10.7
0.3241	12.26	13.04	10.73
0.3269	12.22	13.07	10.75
0.3291	11.89	13.09	10.76
0.3307	9.65	13.1	10.76
0.3362	11.67	13.16	10.79
0.3504	11.66	13.3	10.85
0.3532	11.27	13.33	10.86
0.3597	11.74	13.39	10.89
0.3625	11.27	13.42	10.91
0.3712	11.25	13.51	10.95
0.3871	12.08	13.68	11.1
0.3997	11.37	13.82	10.77
0.4008	11.47	13.83	10.71
0.4030	10.93	13.85	10.56
0.4041	10.69	13.86	10.48
0.4101	10.99	13.93	9.979

0.4123	11.15	13.96	9.766
0.4189	12.35	14.03	9.058
0.4228	12.09	14.07	8.599
0.4386	9.16	14.25	6.604
0.4430	10.10	14.31	6.049
0.4573	11.19	14.47	4.385
0.4622	10.86	14.53	3.889
0.4759	4.33	14.7	2.738
0.4803	5.58	14.75	2.445
0.4934	9.97	14.92	1.779
0.4978	8.66	14.97	1.616
0.5142	2.58	15.19	1.223
0.5427	3.14	15.57	1.025
0.5460	3.03	15.61	1.024
0.5630	2.98	15.85	1.043
0.6140	3.22	16.62	1.199
0.6173	3.27	16.67	1.21
0.6370	3.55	16.98	1.277
0.6381	3.44	17	1.281
0.6600	3.46	17.37	1.356
0.6879	3.92	17.87	1.453
0.7066	3.51	18.22	1.52
0.7109	3.91	18.3	1.535
0.7318	3.55	18.72	1.613
0.7531	3.64	19.17	1.695
0.7575	3.75	19.27	1.712
0.7761	4.01	19.69	1.787
0.7783	4.07	19.74	1.797
0.7844	3.65	19.89	1.822
0.8041	3.94	20.39	1.909
0.8457	3.76	21.59	2.115
0.8709	3.60	22.47	2.262

Data Set 09:

Input Parameters:			
HeatFlux:	36	kWm-2	
MassFlux:	1440	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:	0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1022	13.94	14.830	12.05
0.1033	14.25	14.840	12.05
0.1170	14.17	14.960	12.09
0.1181	13.77	14.970	12.09
0.1225	13.50	15.010	12.1
0.1762	14.67	15.530	12.26
0.1762	14.19	15.530	12.26
0.1899	13.86	15.680	12.31
0.1904	14.14	15.680	12.31
0.1954	13.74	15.730	12.33
0.2304	16.25	16.120	12.45
0.2381	15.78	16.210	12.47
0.2474	14.41	16.320	12.51
0.2507	14.88	16.350	12.52
0.2650	14.13	16.52	12.58

0.2650	13.93	16.52	12.58
0.2677	14.17	16.56	12.59
0.2852	16.31	16.77	12.66
0.3050	16.22	17.02	12.74
0.3082	15.97	17.06	12.75
0.3241	14.67	17.27	12.82
0.3241	15.39	17.27	12.82
0.3389	13.92	17.47	12.88
0.3422	13.80	17.51	12.9
0.3565	16.31	17.71	12.96
0.3603	16.21	17.76	12.98
0.3740	11.11	17.96	13.05
0.3833	10.28	18.09	13.18
0.3965	8.98	18.29	12.99
0.3975	7.76	18.3	12.93
0.4112	3.65	18.5	11.72
0.4151	3.47	18.56	11.24
0.4162	3.20	18.58	11.1
0.4244	2.40	18.71	9.962
0.4348	2.40	18.87	8.395
0.4649	2.32	19.35	4.294
0.4682	2.24	19.4	3.947
0.4814	2.18	19.62	2.807
0.4858	2.13	19.7	2.514
0.5203	2.82	20.29	1.343
0.5285	2.83	20.44	1.261
0.5395	2.52	20.64	1.21
0.5438	2.48	20.72	1.203
0.5548	2.38	20.92	1.207
0.5586	2.38	21	1.213
0.5679	3.09	21.17	1.236
0.5740	3.10	21.29	1.255
0.5899	2.91	21.6	1.31
0.6030	2.91	21.86	1.358
0.6134	2.87	22.08	1.397
0.6288	2.82	22.4	1.456
0.6315	2.82	22.46	1.466
0.6414	3.33	22.67	1.504
0.6496	3.37	22.85	1.535
0.6753	3.29	23.43	1.634
0.6803	3.33	23.54	1.654
0.6857	3.40	23.67	1.675
0.6994	3.21	24	1.728
0.7044	3.30	24.12	1.748
0.7153	3.76	24.39	1.792
0.7224	3.76	24.57	1.821
0.7329	3.74	24.84	1.864
0.7476	3.61	25.24	1.925
0.7548	3.77	25.43	1.956
0.7739	3.66	25.98	2.039
0.7739	3.76	25.98	2.039
0.7931	3.88	26.55	2.127
0.7992	3.88	26.75	2.156
0.8096	3.82	27.08	2.207
0.8211	3.74	27.47	2.265
0.8550	3.92	28.72	2.453
0.8605	3.94	28.95	2.486
0.8698	3.98	29.34	2.546
0.8753	3.97	29.59	2.582
0.8939	3.92	30.49	2.718
0.9257	3.94	32.42	3.01

0.9389	3.94	33.47	3.171
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Data Set 10:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:	0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1082	10.35	11.130	9.953
0.1082	10.49	11.130	9.953
0.1129	10.81	11.150	9.96
0.1263	10.30	11.220	9.981
0.1264	11.57	11.220	9.981
0.1279	10.74	11.230	9.983
0.1768	10.91	11.490	10.07
0.1776	10.54	11.490	10.07
0.1839	10.76	11.530	10.08
0.1925	9.94	11.580	10.1
0.1973	10.12	11.600	10.11
0.1997	10.65	11.620	10.11
0.2415	10.38	11.850	10.2
0.2486	10.63	11.900	10.21
0.2541	10.74	11.93	10.22
0.2604	11.00	11.97	10.24
0.2604	11.16	11.97	10.24
0.2643	10.53	11.99	10.25
0.2707	11.09	12.03	10.26
0.2714	10.22	12.03	10.26
0.2754	10.07	12.06	10.27
0.3132	10.33	12.29	10.36
0.3291	11.67	12.39	10.4
0.3346	11.27	12.43	10.41
0.3353	10.54	12.43	10.41
0.3353	11.07	12.43	10.41
0.3424	10.79	12.48	10.43
0.3456	10.56	12.5	10.44
0.3464	10.76	12.5	10.44
0.3891	12.68	12.79	10.56
0.3897	10.51	12.79	10.56
0.3929	10.42	12.81	10.57
0.3992	10.65	12.86	10.59
0.3993	12.93	12.86	10.59
0.4031	10.30	12.88	10.6
0.4032	10.93	12.88	10.6
0.4032	11.13	12.88	10.6
0.4055	10.81	12.9	10.61
0.4079	10.77	12.92	10.61
0.4110	9.75	12.94	10.62
0.4134	9.87	12.95	10.63
0.4150	10.35	12.97	10.64
0.4157	10.17	12.97	10.64
0.4220	9.57	13.02	10.66
0.4585	12.77	13.28	10.77
0.4703	12.56	13.37	10.81

0.4710	10.63	13.37	10.81
0.4734	11.32	13.39	10.82
0.4757	11.07	13.41	10.83
0.4780	9.93	13.42	10.84
0.4804	10.70	13.44	10.84
0.4813	11.20	13.45	10.85
0.4860	11.59	13.49	10.86
0.4970	10.72	13.57	10.9
0.5318	11.60	13.85	11.03
0.5380	10.97	13.9	11.06
0.5406	14.17	13.92	11.07
0.5491	12.01	13.99	11.1
0.5500	14.06	13.99	11.1
0.5522	10.61	14.01	11.11
0.5546	11.00	14.03	11.12
0.5578	12.79	14.06	11.13
0.5602	11.96	14.08	11.14
0.5688	11.69	14.15	11.18
0.6036	12.89	14.46	11.37
0.6147	14.52	14.56	11.38
0.6163	14.08	14.57	11.34
0.6209	11.04	14.62	11.13
0.6217	12.47	14.62	11.08
0.6265	14.43	14.67	10.74
0.6272	10.86	14.67	10.69
0.6281	13.92	14.68	10.61
0.6336	12.82	14.73	10.1
0.6405	8.92	14.8	9.346
0.6709	1.60	15.1	5.458
0.6819	1.85	15.21	4.213
0.6859	1.76	15.25	3.811
0.6937	1.46	15.34	3.122
0.6953	1.32	15.35	2.996
0.6961	1.66	15.36	2.934
0.6961	1.81	15.36	2.934
0.7024	1.32	15.43	2.496
0.7119	1.34	15.53	1.974
0.7466	1.30	15.94	1.132
0.7545	1.39	16.03	1.083
0.7639	1.21	16.15	1.059
0.7734	1.25	16.28	1.059
0.7750	1.37	16.3	1.061
0.7836	1.34	16.41	1.076
0.7915	1.25	16.52	1.096
0.8018	1.25	16.67	1.128
0.8089	1.266	16.78	1.152
0.8097	1.266	16.79	1.155
0.8128	1.266	16.84	1.166
0.8483	1.195	17.43	1.301
0.8885	1.248	18.28	1.474
0.9224	1.142	19.26	1.652

Data Set 11:

Input Parameters:			
HeatFlux:	36	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:		0	%
Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1173	15.99	16.380	13.77
0.1180	15.60	16.390	13.77
0.1188	15.83	16.390	13.77
0.1195	15.47	16.400	13.77
0.1525	15.73	16.650	13.83
0.1547	16.30	16.660	13.83
0.1547	15.48	16.660	13.83
0.1598	15.21	16.700	13.84
0.1679	15.19	16.770	13.85
0.1694	14.98	16.780	13.86
0.1708	14.77	16.790	13.86
0.1870	15.85	16.920	13.89
0.1884	15.71	16.930	13.89
0.1928	16.05	16.960	13.9
0.2046	15.48	17.06	13.92
0.2053	15.27	17.06	13.92
0.2089	14.93	17.09	13.93
0.2273	16.47	17.24	13.97
0.2324	16.09	17.29	13.98
0.2331	15.90	17.29	13.98
0.2368	16.23	17.32	13.99
0.2405	15.79	17.35	13.99
0.2412	15.27	17.36	14
0.2419	15.60	17.37	14
0.2493	14.95	17.43	14.01
0.2515	14.77	17.45	14.02
0.2522	15.43	17.45	14.02
0.2573	15.33	17.5	14.03
0.2610	15.78	17.53	14.04
0.2647	15.97	17.56	14.05
0.2713	15.43	17.61	14.06
0.2742	15.98	17.64	14.07
0.2742	15.67	17.64	14.07
0.2742	15.27	17.64	14.07
0.2830	15.53	17.72	14.09
0.2830	15.41	17.72	14.09
0.2859	14.81	17.74	14.1
0.2874	14.50	17.75	14.1
0.2903	15.19	17.78	14.11
0.2903	15.00	17.78	14.11
0.2911	15.84	17.79	14.11
0.3013	15.83	17.88	14.13
0.3028	15.88	17.89	14.14
0.3035	16.28	17.9	14.14
0.3116	15.32	17.97	14.16
0.3138	15.03	17.99	14.16
0.3160	14.65	18.01	14.17
0.3306	15.41	18.14	14.2
0.3321	15.58	18.15	14.21
0.3365	15.81	18.19	14.22
0.3387	16.00	18.21	14.22
0.3416	15.55	18.24	14.23
0.3416	15.38	18.24	14.23
0.3416	15.84	18.24	14.23
0.3424	15.13	18.24	14.23
0.3519	14.94	18.33	14.26
0.3519	14.84	18.33	14.26

0.3541	15.12	18.35	14.26
0.3600	15.41	18.41	14.28
0.3658	15.53	18.46	14.3
0.3680	15.34	18.48	14.3
0.3688	15.70	18.49	14.3
0.3746	15.55	18.54	14.32
0.3746	15.91	18.54	14.32
0.3783	15.15	18.58	14.33
0.3842	15.43	18.63	14.35
0.3842	15.15	18.63	14.35
0.3842	15.38	18.63	14.35
0.3878	14.94	18.67	14.36
0.3893	14.79	18.68	14.36
0.3908	14.68	18.7	14.37
0.3974	15.01	18.76	14.38
0.4018	15.25	18.8	14.4
0.4069	15.43	18.85	14.41
0.4091	15.79	18.87	14.42
0.4113	15.81	18.89	14.43
0.4157	15.48	18.94	14.44
0.4186	15.32	18.96	14.45
0.4201	15.17	18.98	14.45
0.4230	15.01	19.01	14.46
0.4267	14.86	19.04	14.47
0.4289	14.70	19.07	14.48
0.4377	14.98	19.15	14.51
0.4377	15.34	19.15	14.51
0.4384	15.13	19.16	14.51
0.4391	15.55	19.17	14.51
0.4428	15.72	19.2	14.52
0.4435	17.47	19.21	14.52
0.4487	16.57	19.26	14.54
0.4567	15.25	19.34	14.57
0.4575	14.91	19.35	14.57
0.4633	14.56	19.41	14.59
0.4699	15.93	19.48	14.61
0.4721	14.96	19.5	14.62
0.4773	15.94	19.55	14.64
0.4919	15.77	19.71	14.69
0.4978	15.51	19.77	14.71
0.4985	15.32	19.78	14.71
0.5044	16.31	19.84	14.73
0.5088	14.92	19.89	14.75
0.5154	16.5	19.96	14.77
0.5169	16.1	19.97	14.78
0.5176	16.31	19.98	14.78
0.5205	15.86	20.01	14.79
0.5249	15.67	20.06	14.81
0.5403	15.98	20.23	14.87
0.544	15.98	20.27	14.88
0.5469	15.89	20.3	14.89
0.5623	15.99	20.48	14.95
0.5667	15.53	20.53	14.97
0.5667	15.34	20.53	14.97
0.5726	11.12	20.59	15
0.5821	10.24	20.7	15.04
0.5843	7.435	20.73	15.05
0.5894	7.694	20.79	15.07
0.5902	9.337	20.8	15.07
0.5924	8.04	20.82	15.08
0.5931	8.144	20.83	15.09

0.5982	2.161	20.89	15.12
0.6349	1.676	21.34	13.26
0.6466	1.71	21.49	11.42
0.6598	1.537	21.66	9.121
0.6635	1.849	21.7	8.474
0.6708	1.675	21.8	7.251
0.6759	1.554	21.87	6.444
0.7067	1.277	22.29	2.956
0.7163	1.312	22.42	2.353
0.7236	1.311	22.53	2.021
0.7324	1.398	22.66	1.738
0.7456	1.328	22.86	1.498
0.7786	1.241	23.38	1.391
0.7866	1.241	23.52	1.412
0.8006	1.189	23.76	1.462
0.8057	1.31	23.85	1.483
0.8116	1.362	23.96	1.509
0.8204	1.361	24.12	1.547
0.8482	1.153	24.69	1.676
0.8541	1.153	24.82	1.705
0.8585	1.101	24.92	1.726
0.8688	1.153	25.16	1.777
0.8746	1.205	25.3	1.806
0.9311	1.221	27.12	2.142
0.9391	1.204	27.5	2.203
0.9435	1.1	27.73	2.24

Data Set 12:

Input Parameters:			
HeatFlux:	9	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:	0.5	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1807	3.39	3.006	3.482
0.1993	3.39	3.030	3.498
0.2420	3.23	3.089	3.535
0.2553	3.46	3.108	3.547
0.2686	3.53	3.128	3.56
0.2779	3.18	3.142	3.568
0.3139	3.58	3.199	3.603
0.3272	3.39	3.221	3.616
0.3379	3.53	3.238	3.627
0.3579	3.56	3.273	3.647
0.3872	3.44	3.326	3.677
0.4018	3.56	3.353	3.693
0.4072	3.60	3.363	3.699
0.4325	3.44	3.412	3.727
0.4671	3.58	3.484	3.768
0.4738	3.81	3.498	3.776
0.4778	4.04	3.507	3.78
0.5124	3.60	3.585	3.824
0.5457	3.86	3.665	3.869
0.5470	4.09	3.669	3.871
0.5857	3.97	3.77	3.929

0.6137	4.39	3.85	3.974
0.6177	4.25	3.862	3.981
0.6603	4.16	3.996	4.059
0.6829	4.67	4.074	4.105
0.6923	4.58	4.109	4.125
0.7402	4.37	4.302	4.243
0.7495	4.79	4.344	4.27
0.7602	3.62	4.394	3.151
0.7642	4.72	4.413	1.742
0.8068	1.26	4.644	1.249
0.8281	1.03	4.781	1.166
0.8401	1.23	4.866	1.119
0.8921	0.70	5.347	0.9077
0.9640	0.56	6.893	0.6033

Data Set 13:

Input Parameters:			
HeatFlux:	9	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:	1.0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1727	3.02	2.993	3.323
0.1967	3.07	3.024	3.343
0.2273	2.95	3.065	3.37
0.2420	3.21	3.086	3.384
0.2659	3.18	3.121	3.406
0.2993	3.21	3.172	3.438
0.3179	3.07	3.202	3.457
0.3272	3.28	3.217	3.466
0.3405	2.93	3.239	3.479
0.3712	3.21	3.292	3.512
0.3912	3.18	3.329	3.533
0.3992	3.32	3.344	3.542
0.4072	3.23	3.359	3.551
0.4458	3.37	3.435	3.595
0.4658	3.37	3.476	3.619
0.4818	3.93	3.511	3.639
0.5191	3.81	3.595	3.688
0.5311	3.42	3.624	3.705
0.5457	3.79	3.66	3.725
0.5883	3.90	3.771	3.79
0.6003	3.81	3.805	3.809
0.6057	3.72	3.82	3.818
0.6177	4.00	3.855	3.839
0.6616	4.18	3.993	3.921
0.6789	3.93	4.052	3.957
0.6856	4.28	4.076	3.971
0.6936	4.46	4.105	3.989
0.7336	4.65	4.263	4.088
0.7522	4.07	4.345	4.141
0.7602	5.04	4.382	3.051
0.8055	2.19	4.622	1.216
0.8215	1.03	4.721	1.157
0.8361	0.98	4.82	1.102

0.8761	0.70	5.152	0.9476
0.9041	0.65	5.467	0.8352

Data Set 14:

Input Parameters:			
HeatFlux:	9	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:

OCR_exp:	5.0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1767	2.98	2.975	3.026
0.2033	3.00	3.008	3.049
0.2473	2.79	3.067	3.09
0.2486	3.16	3.069	3.092
0.2713	3.09	3.102	3.114
0.3219	3.04	3.179	3.165
0.3485	3.18	3.222	3.193
0.3485	3.00	3.222	3.193
0.3965	3.30	3.305	3.247
0.4005	3.04	3.312	3.251
0.4231	3.11	3.354	3.278
0.4231	3.35	3.354	3.278
0.4698	3.49	3.446	3.336
0.4764	3.32	3.459	3.344
0.4831	3.56	3.473	3.353
0.5017	3.25	3.513	3.378
0.5351	3.56	3.588	3.425
0.5524	3.46	3.629	3.451
0.5670	3.51	3.665	3.474
0.5777	3.51	3.692	3.491
0.6110	3.67	3.78	3.548
0.6336	3.63	3.844	3.589
0.6496	3.53	3.891	3.62
0.6803	3.86	3.988	3.685
0.7016	3.83	4.06	3.734
0.7082	4.00	4.084	3.751
0.7229	3.83	4.138	3.788
0.7789	3.53	4.371	1.229
0.7789	3.90	4.371	1.229
0.7988	2.91	4.468	1.164
0.8215	1.40	4.589	1.087
0.8468	1.07	4.743	1
0.8774	0.84	4.964	0.8907
0.9334	0.93	5.507	0.6807
0.9507	0.70	5.632	0.615

Data Set 15:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	4	mm	

OCR's:

OCR_exp:	1.0	%
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Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0903	3.54	3.855	3.864
0.0942	3.63	3.862	3.866
0.1164	3.72	3.905	3.878
0.1747	3.55	4.029	3.902
0.1808	3.62	4.043	3.904
0.2000	3.72	4.089	3.908
0.2199	3.64	4.138	3.911
0.2644	3.72	4.254	3.912
0.2706	3.81	4.271	3.911
0.3504	3.98	4.508	3.894
0.3580	4.05	4.533	3.891
0.3742	4.06	4.586	3.886
0.3941	4.07	4.653	3.878
0.4393	3.96	4.815	3.857
0.4439	4.03	4.832	3.855
0.4662	3.98	4.918	3.844
0.4861	4.05	4.997	3.834
0.5252	3.80	5.162	3.815
0.5298	3.88	5.183	3.813
0.5536	3.83	5.291	3.802
0.5682	3.83	5.359	3.796
0.6151	4.93	5.596	3.78
0.6182	5.08	5.613	3.779
0.6426	3.93	5.748	3.774
0.6602	3.50	5.85	3.773
0.7045	1.91	6.131	1.933
0.7290	1.65	6.303	2.008
0.7467	1.69	6.437	2.033
0.7935	1.85	6.838	2.114
0.8165	1.87	7.069	2.163
0.8318	1.86	7.239	2.202
0.8809	1.92	7.915	2.366
0.8993	1.89	8.248	2.455
0.9193	1.86	8.696	2.58

Data Set 16:

Input Parameters:		
HeatFlux:	18	kWm-2
MassFlux:	720	kgm-2s-1
T_sat:	15	C
Diameter:	4	mm

OCR's:		
OCR_exp:	3.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1010	3.45	3.865	3.516
0.1194	3.47	3.901	3.528
0.1470	3.33	3.957	3.543
0.1839	3.42	4.039	3.559
0.2015	3.53	4.080	3.565
0.2115	3.49	4.105	3.568
0.2299	3.45	4.150	3.573
0.2759	3.54	4.272	3.579
0.2905	3.62	4.313	3.58

0.3012	3.62	4.343	3.58
0.3212	3.59	4.402	3.58
0.3672	3.67	4.545	3.575
0.3810	3.69	4.590	3.572
0.3887	3.74	4.616	3.571
0.4109	3.74	4.692	3.566
0.4516	3.69	4.84	3.556
0.4761	3.67	4.934	3.55
0.5007	3.70	5.033	3.543
0.5367	3.49	5.186	3.534
0.5528	3.58	5.258	3.531
0.5666	3.54	5.322	3.528
0.5889	3.51	5.428	3.525
0.6287	3.54	5.632	3.523
0.6425	3.16	5.707	3.524
0.6555	3.14	5.781	3.526
0.6715	1.85	5.874	3.529
0.7137	1.78	6.141	1.865
0.7275	1.79	6.236	1.884
0.7467	1.79	6.375	1.912
0.7705	1.81	6.562	1.951
0.8042	2.02	6.857	2.018
0.8364	1.95	7.187	2.098
0.8518	1.91	7.367	2.144
0.8917	1.95	7.931	2.302
0.9070	1.91	8.201	2.386
0.9239	1.92	8.554	2.503
0.9400	1.89	8.962	2.652

Data Set 17:

Input Parameters:		
HeatFlux:	18	kWm-2
MassFlux:	720	kgm-2s-1
T_sat:	15	C
Diameter:	4	mm

OCR's:		
OCR_exp:	5.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0972	3.50	3.848	3.568
0.1148	3.48	3.881	3.579
0.1317	3.56	3.915	3.588
0.1409	3.50	3.934	3.593
0.1893	3.55	4.040	3.614
0.2031	3.56	4.072	3.618
0.2161	3.51	4.103	3.621
0.2307	3.51	4.139	3.625
0.2844	3.78	4.281	3.63
0.2928	3.66	4.305	3.63
0.3074	3.86	4.346	3.63
0.3212	3.71	4.386	3.629
0.3757	3.78	4.555	3.621
0.3872	3.87	4.593	3.618
0.4063	3.78	4.657	3.614
0.4631	3.78	4.861	3.598
0.4792	3.81	4.923	3.593
0.4976	3.73	4.995	3.587
0.5559	3.54	5.242	3.572

0.5643	3.47	5.28	3.57
0.5873	3.31	5.387	3.566
0.6432	2.12	5.671	3.562
0.6447	2.00	5.679	3.562
0.6448	2.57	5.679	3.562
0.6777	1.85	5.865	3.568
0.7252	2.00	6.163	1.899
0.7298	1.93	6.194	1.905
0.7659	1.97	6.453	1.961
0.8088	2.11	6.81	2.046
0.8257	2.00	6.969	2.087
0.8526	2.04	7.249	2.164
0.8986	2.12	7.842	2.355
0.8993	2.06	7.853	2.359
0.9155	2.03	8.105	2.458
0.9415	1.91	8.516	2.686

Data Set 18:

Input Parameters:		
HeatFlux:	18	kWm-2
MassFlux:	720	kgm-2s-1
T_sat:	15	C
Diameter:	6	mm

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0390	3.16	3.421	3.428
0.0594	3.17	3.439	3.438
0.0653	3.17	3.445	3.44
0.0791	3.17	3.460	3.445
0.0857	3.17	3.468	3.447
0.1035	3.21	3.490	3.451
0.1252	3.19	3.520	3.453
0.1305	3.27	3.528	3.453
0.1469	3.25	3.553	3.452
0.1541	3.31	3.565	3.451
0.1699	3.32	3.592	3.447
0.1699	3.26	3.592	3.447
0.1936	3.32	3.635	3.438
0.2015	3.32	3.650	3.435
0.2193	3.24	3.685	3.425
0.2325	3.21	3.713	3.417
0.2417	3.20	3.733	3.41
0.2555	3.23	3.763	3.4
0.2739	3.22	3.806	3.384
0.2825	3.24	3.827	3.376
0.2858	3.23	3.835	3.373
0.3049	3.76	3.883	3.355
0.3075	3.79	3.89	3.352
0.3292	3.73	3.948	3.329
0.3305	3.78	3.951	3.327
0.3483	3.63	4.001	3.307
0.3522	3.70	4.013	3.302
0.3700	3.45	4.065	3.281
0.3746	3.42	4.079	3.275
0.3845	3.67	4.11	3.263
0.3878	3.58	4.12	3.258

0.4174	3.42	4.216	3.22
0.4187	3.38	4.221	3.218
0.4358	3.58	4.279	3.196
0.4378	3.62	4.286	3.193
0.4589	3.37	4.362	3.165
0.4615	3.35	4.372	3.161
0.5214	3.57	4.609	3.082
0.5240	3.57	4.62	3.078
0.5471	3.38	4.721	3.049
0.5484	3.35	4.727	3.047
0.6096	3.53	5.023	2.975
0.6129	3.50	5.04	2.972
0.6372	3.48	5.172	2.947
0.6385	3.43	5.179	2.946
0.7004	3.04	5.556	2.898
0.7024	3.07	5.57	2.897
0.7248	2.85	5.725	2.886
0.7274	2.76	5.744	2.885
0.7873	1.91	6.23	1.891
0.7945	1.94	6.296	1.889
0.8123	2.04	6.471	1.884
0.8195	2.03	6.546	1.883
0.8722	1.94	7.206	1.893
0.8728	1.99	7.215	1.894
0.9031	2.03	7.735	1.927
0.9071	2.01	7.816	1.935

Data Set 19:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	6	mm	

OCR's:		
OCR_exp:	3.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0482	2.86	3.421	3.107
0.0581	2.86	3.430	3.112
0.0633	2.86	3.435	3.115
0.0870	2.89	3.461	3.125
0.0962	2.94	3.472	3.128
0.1061	2.90	3.485	3.13
0.1318	2.89	3.521	3.135
0.1462	2.91	3.544	3.136
0.1561	2.95	3.559	3.136
0.1851	3.10	3.610	3.132
0.1851	3.10	3.610	3.132
0.1982	3.10	3.634	3.129
0.2200	2.94	3.677	3.121
0.2259	2.96	3.689	3.119
0.2390	2.98	3.717	3.113
0.2601	3.01	3.763	3.101
0.2733	3.04	3.794	3.093
0.2772	3.06	3.803	3.09
0.2910	3.03	3.837	3.081
0.3101	3.24	3.885	3.066
0.3193	3.23	3.909	3.059

0.3575	3.09	4.015	3.025
0.3654	3.15	4.038	3.017
0.3753	3.16	4.068	3.007
0.3963	3.06	4.133	2.986
0.4088	3.06	4.173	2.974
0.4115	3.07	4.181	2.971
0.4240	3.03	4.223	2.958
0.4398	3.07	4.277	2.941
0.4529	3.03	4.323	2.927
0.4674	3.03	4.376	2.911
0.5280	3.04	4.615	2.847
0.5411	3.06	4.672	2.834
0.5582	3.06	4.748	2.817
0.6181	2.90	5.038	2.764
0.6241	2.85	5.068	2.759
0.6287	2.81	5.093	2.756
0.6478	2.82	5.197	2.742
0.7011	2.45	5.517	2.715
0.7103	2.37	5.577	2.712
0.7182	2.35	5.631	2.71
0.7373	2.40	5.764	2.128
0.7873	1.81	6.16	1.784
0.7971	1.81	6.247	1.782
0.8024	1.79	6.295	1.781
0.8235	1.80	6.5	1.781
0.8774	1.88	7.145	1.805
0.8821	1.90	7.211	1.81
0.8893	1.85	7.32	1.818
0.9156	1.90	7.779	1.867

Data Set 20:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	6	mm	

OCR's:		
OCR_exp:	5.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.0521	2.94	3.424	3.159
0.0594	2.87	3.431	3.162
0.0627	2.98	3.434	3.164
0.0890	2.93	3.464	3.174
0.1008	2.94	3.478	3.178
0.1087	2.94	3.489	3.18
0.1357	3.01	3.527	3.184
0.1456	3.02	3.542	3.184
0.1462	2.88	3.544	3.184
0.1838	3.11	3.607	3.179
0.1864	3.11	3.612	3.179
0.1963	3.10	3.630	3.176
0.2206	3.22	3.678	3.167
0.2246	3.20	3.686	3.165
0.2344	3.19	3.707	3.161
0.2680	3.15	3.781	3.141
0.2739	3.13	3.795	3.137
0.2766	3.13	3.802	3.135

0.3160	3.20	3.9	3.104
0.3207	3.20	3.913	3.1
0.3220	3.20	3.916	3.099
0.3496	3.00	3.992	3.074
0.3582	3.01	4.017	3.065
0.3641	3.01	4.034	3.059
0.4023	2.84	4.152	3.02
0.4075	2.87	4.168	3.014
0.4102	2.87	4.177	3.011
0.4418	2.81	4.284	2.977
0.4497	2.81	4.312	2.968
0.4556	2.78	4.333	2.961
0.5359	2.81	4.649	2.873
0.5372	2.80	4.655	2.872
0.5385	2.78	4.66	2.871
0.6162	2.57	5.027	2.796
0.6227	2.57	5.062	2.791
0.6313	2.60	5.107	2.784
0.7076	2.33	5.56	2.74
0.7162	2.33	5.617	2.738
0.7188	2.30	5.635	2.737
0.7912	1.83	6.194	1.799
0.7978	1.84	6.253	1.798
0.8050	1.87	6.32	1.797
0.8788	1.84	7.163	1.82
0.8840	1.84	7.24	1.825
0.8867	1.84	7.28	1.829

Data Set 21:

Input Parameters:			
HeatFlux:	4.5	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1047	2.96	2.539	2.814
0.1378	2.88	2.573	2.844
0.1421	2.92	2.578	2.848
0.1741	2.68	2.614	2.879
0.1817	2.84	2.623	2.887
0.1953	2.84	2.640	2.902
0.2115	3.19	2.660	2.919
0.2169	2.67	2.667	2.925
0.2348	2.75	2.690	2.945
0.2468	2.91	2.706	2.959
0.2544	3.21	2.716	2.968
0.2674	2.81	2.735	2.983
0.2815	3.22	2.755	3.001
0.2896	2.91	2.766	3.011
0.3070	3.26	2.792	3.033
0.3195	3.33	2.812	3.049
0.3281	3.23	2.825	3.061
0.3449	3.13	2.852	3.084
0.3542	3.34	2.867	3.097
0.3672	3.30	2.889	3.115

0.3810	3.20	2.912	3.135
0.3889	3.34	2.926	3.147
0.4016	3.55	2.949	3.166
0.4182	3.37	2.979	3.192
0.4285	3.47	2.998	3.209
0.4388	3.35	3.018	3.225
0.4572	3.34	3.054	3.256
0.4789	3.39	3.098	3.294
0.4930	3.52	3.128	3.319
0.5299	3.81	3.211	3.389
0.5700	4.10	3.308	3.472
0.6036	4.40	3.397	3.548
0.6253	4.17	3.459	3.601
0.6378	4.48	3.497	3.633
0.6807	4.39	3.636	3.752
0.6980	4.51	3.697	3.806
0.7110	4.93	3.746	3.848
0.7533	4.71	3.923	4.003
0.7685	4.81	3.994	1.554
0.7745	4.73	4.024	0.8553
0.8271	4.39	4.327	1.035
0.8303	4.30	4.349	1.025

Data Set 22:

Input Parameters:			
HeatFlux:	9	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1741	3.09	2.995	3.324
0.2001	3.13	3.028	3.346
0.2300	2.97	3.069	3.373
0.2468	3.23	3.093	3.388
0.2560	3.05	3.106	3.397
0.2685	3.22	3.124	3.409
0.3026	3.25	3.177	3.441
0.3200	3.12	3.205	3.459
0.3287	3.31	3.219	3.467
0.3368	3.00	3.233	3.476
0.3753	3.20	3.300	3.516
0.3889	3.16	3.325	3.531
0.4013	3.29	3.348	3.544
0.4122	3.29	3.368	3.556
0.4453	3.42	3.434	3.595
0.4605	3.43	3.465	3.613
0.4746	3.50	3.495	3.63
0.4800	4.00	3.507	3.637
0.5180	3.75	3.593	3.687
0.5353	3.45	3.634	3.71
0.5445	3.87	3.657	3.724
0.5527	3.79	3.677	3.735
0.5917	3.87	3.781	3.795
0.6085	3.75	3.828	3.823
0.6161	4.00	3.85	3.836

0.6205	4.13	3.863	3.844
0.6633	4.25	3.998	3.924
0.6774	3.96	4.047	3.954
0.6910	4.35	4.095	3.983
0.6942	4.54	4.107	3.991
0.7330	4.63	4.26	4.086
0.7506	4.08	4.338	4.136
0.7636	5.04	4.398	3.33
0.7636	4.95	4.398	3.33
0.8065	2.22	4.627	1.212
0.8227	1.09	4.728	1.152
0.8320	1.12	4.791	1.118
0.8320	0.99	4.791	1.118
0.8792	0.75	5.183	0.9353
0.9041	0.66	5.467	0.8352

Data Set 23:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.2039	4.885	3.675	4.048
0.2289	4.586	3.713	4.057
0.2386	4.303	3.728	4.06
0.2593	4.303	3.760	4.067
0.269	4.088	3.776	4.069
0.2766	4.219	3.789	4.072
0.294	4.298	3.818	4.076
0.2988	3.967	3.826	4.078
0.3026	4.004	3.833	4.079
0.3113	4.124	3.848	4.081
0.3319	3.878	3.885	4.085
0.3325	3.957	3.886	4.085
0.3417	3.962	3.902	4.087
0.3498	4.182	3.917	4.089
0.3715	3.846	3.959	4.093
0.3721	3.883	3.96	4.093
0.3797	3.999	3.974	4.095
0.3834	4.172	3.982	4.095
0.4057	3.951	4.026	4.099
0.41	3.789	4.035	4.1
0.4149	4.056	4.045	4.1
0.423	4.25	4.062	4.102
0.4436	3.957	4.106	4.105
0.4491	3.899	4.118	4.105
0.4529	4.14	4.127	4.106
0.4572	4.161	4.136	4.107
0.4767	4.061	4.18	4.109
0.4827	3.957	4.194	4.11
0.4881	4.135	4.207	4.111
0.4968	4.13	4.227	4.113
0.518	4.009	4.279	4.116
0.5223	4.041	4.29	4.117

0.5261	4.13	4.299	4.118
0.5304	4.109	4.31	4.118
0.5521	3.962	4.367	4.123
0.5603	4.056	4.389	4.125
0.5917	3.957	4.477	4.133
0.6004	4.02	4.502	4.135
0.602	4.082	4.507	4.136
0.6346	4.088	4.608	4.148
0.6346	4.014	4.608	4.148
0.6633	4.172	4.704	4.162
0.6796	4.219	4.762	4.172
0.7072	4.14	4.867	4.192
0.7116	3.857	4.885	4.196
0.7376	3.799	4.995	4.221
0.7501	4.177	5.051	4.235
0.7799	1.931	5.198	1.506
0.7842	1.213	5.221	1.487
0.8097	1.307	5.367	1.376
0.8238	1.139	5.457	1.313
0.8537	0.9189	5.675	1.177
0.8613	1.05	5.738	1.142
0.8829	0.793	5.94	1.04
0.8965	0.8874	6.09	0.9756
0.9258	0.7667	6.503	0.8334
0.9339	0.667	6.651	0.7937
0.9513	0.6723	7.052	0.709

Data Set 24:

Input Parameters:			
HeatFlux:	36	kWm-2	
MassFlux:	360	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.2169	5.84	4.773	5.133
0.2207	5.76	4.780	5.129
0.2511	5.76	4.834	5.094
0.2896	5.68	4.906	5.042
0.2945	5.63	4.916	5.035
0.3243	5.59	4.975	4.988
0.3628	5.64	5.055	4.922
0.3672	5.59	5.065	4.914
0.3976	5.64	5.132	4.858
0.4361	5.61	5.221	4.782
0.4361	5.64	5.221	4.782
0.4702	5.64	5.304	4.713
0.5093	5.47	5.406	4.632
0.5429	5.52	5.499	4.562
0.5776	5.31	5.601	4.491
0.5814	5.33	5.612	4.483
0.6123	5.38	5.709	4.422
0.6514	5.13	5.839	4.348
0.6519	5.22	5.841	4.348
0.6855	5.35	5.96	4.29
0.7240	4.96	6.104	4.231

0.7240	5.10	6.104	4.231
0.7588	5.43	6.24	4.188
0.7967	4.89	6.397	1.731
0.7973	4.93	6.4	1.727
0.8320	4.72	6.55	1.531
0.8661	4.55	6.704	1.332
0.8661	1.13	6.704	1.332
0.9008	1.27	6.868	1.126

Data Set 25:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	1440	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1081	6.37	6.902	6.938
0.1349	6.63	6.992	6.994
0.1432	7.07	7.022	7.012
0.1706	7.38	7.124	7.07
0.1795	7.07	7.158	7.089
0.2049	7.22	7.261	7.144
0.2139	7.62	7.298	7.163
0.2543	7.38	7.476	7.25
0.2543	7.90	7.476	7.25
0.2797	7.60	7.595	7.305
0.2892	7.32	7.641	7.326
0.3153	7.32	7.772	7.382
0.3242	7.55	7.818	7.402
0.3283	7.12	7.839	7.411
0.3503	7.49	7.957	7.459
0.3625	7.12	8.025	7.485
0.3640	7.87	8.033	7.489
0.3893	7.39	8.179	2.434
0.3982	6.86	8.232	2.847
0.4236	2.74	8.387	2.864
0.4332	2.64	8.448	2.87
0.4368	3.74	8.471	2.873
0.4579	2.78	8.61	2.889
0.4709	2.57	8.698	2.899
0.5079	2.85	8.962	2.931
0.5773	3.39	9.517	3.002
0.6047	3.60	9.762	3.035
0.6527	3.79	10.23	3.103
0.6534	3.71	10.24	3.104
0.6747	3.97	10.47	3.138
0.7234	4.28	11.06	3.232
0.7282	4.08	11.12	3.242
0.7454	4.43	11.36	3.282
0.7940	4.27	12.13	3.42
0.7981	4.46	12.21	3.433
0.8201	4.45	12.63	3.514
0.8722	4.49	13.91	3.778

Data Set 26:

Input Parameters:			
HeatFlux:	36	kWm-2	
MassFlux:	1440	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:			
Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1747	6.90	7.761	7.351
0.1959	6.90	7.855	7.365
0.2220	6.86	7.977	7.378
0.2494	7.12	8.112	7.386
0.2542	6.81	8.136	7.387
0.2714	7.12	8.225	7.388
0.2960	6.60	8.358	7.388
0.3228	7.13	8.510	7.383
0.3323	6.39	8.565	7.38
0.3446	6.08	8.638	7.376
0.3720	6.08	8.807	7.365
0.4071	2.59	9.037	2.959
0.4668	2.53	9.461	2.999
0.4942	2.58	9.672	3.021
0.5162	2.70	9.85	3.039
0.5374	2.73	10.03	3.059
0.5552	2.80	10.19	3.077
0.5703	2.85	10.32	3.092
0.5902	2.95	10.51	3.115
0.6081	3.16	10.68	3.136
0.6300	3.05	10.91	3.165
0.6396	3.23	11.01	3.178
0.6616	3.39	11.24	3.211
0.6781	3.60	11.42	3.238
0.7055	3.44	11.73	3.287
0.7130	3.60	11.82	3.302
0.7350	3.71	12.08	3.349
0.7542	3.92	12.32	3.394
0.7754	3.70	12.59	3.451
0.7850	3.90	12.71	3.48
0.8056	3.89	12.99	3.547
0.8235	4.12	13.23	3.615
0.8502	3.90	13.6	3.737
0.8605	4.07	13.75	3.792
0.8803	4.01	14.04	3.917
0.9249	3.91	14.71	4.346

Data Set 27:

Input Parameters:			
HeatFlux:	18	kWm-2	
MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

OCR's:		
OCR_exp:	1.0	%

Data:

Quality	HTC_Dang	HTC_Aiyo	HTC_new
0.1875	4.62	4.914	4.885
0.2002	4.67	4.945	4.899
0.2262	4.90	5.013	4.927
0.2571	4.69	5.097	4.959
0.2606	4.88	5.107	4.963
0.2740	4.95	5.145	4.977
0.2965	5.04	5.211	5
0.3316	4.71	5.319	5.036
0.3351	4.92	5.330	5.039
0.3443	4.94	5.359	5.049
0.3710	4.98	5.447	5.076
0.4055	4.61	5.567	5.111
0.4090	5.32	5.580	5.114
0.4188	5.25	5.615	5.124
0.4406	5.47	5.697	5.147
0.4751	5.27	5.832	5.183
0.4849	5.74	5.872	5.194
0.4884	5.66	5.887	5.198
0.5144	5.88	5.997	5.227
0.5496	5.64	6.156	5.27
0.5587	6.10	6.199	5.281
0.5636	6.27	6.223	5.288
0.5897	5.15	6.352	5.323
0.6241	1.64	6.536	2.035
0.6332	1.36	6.587	2.032
0.6593	1.27	6.741	2.024
0.6983	1.22	6.993	2.016
0.7057	1.09	7.044	2.015
0.7078	1.15	7.059	2.014
0.7296	1.16	7.22	2.012
0.7689	1.22	7.544	2.014
0.7774	1.10	7.621	2.015
0.7823	1.05	7.667	2.016
0.8034	1.16	7.879	2.023
0.8435	1.25	8.355	2.049
0.8484	1.14	8.422	2.054
0.8519	1.10	8.471	2.058
0.8730	1.21	8.799	2.086
0.9131	1.26	9.634	2.182

Data Set 28:

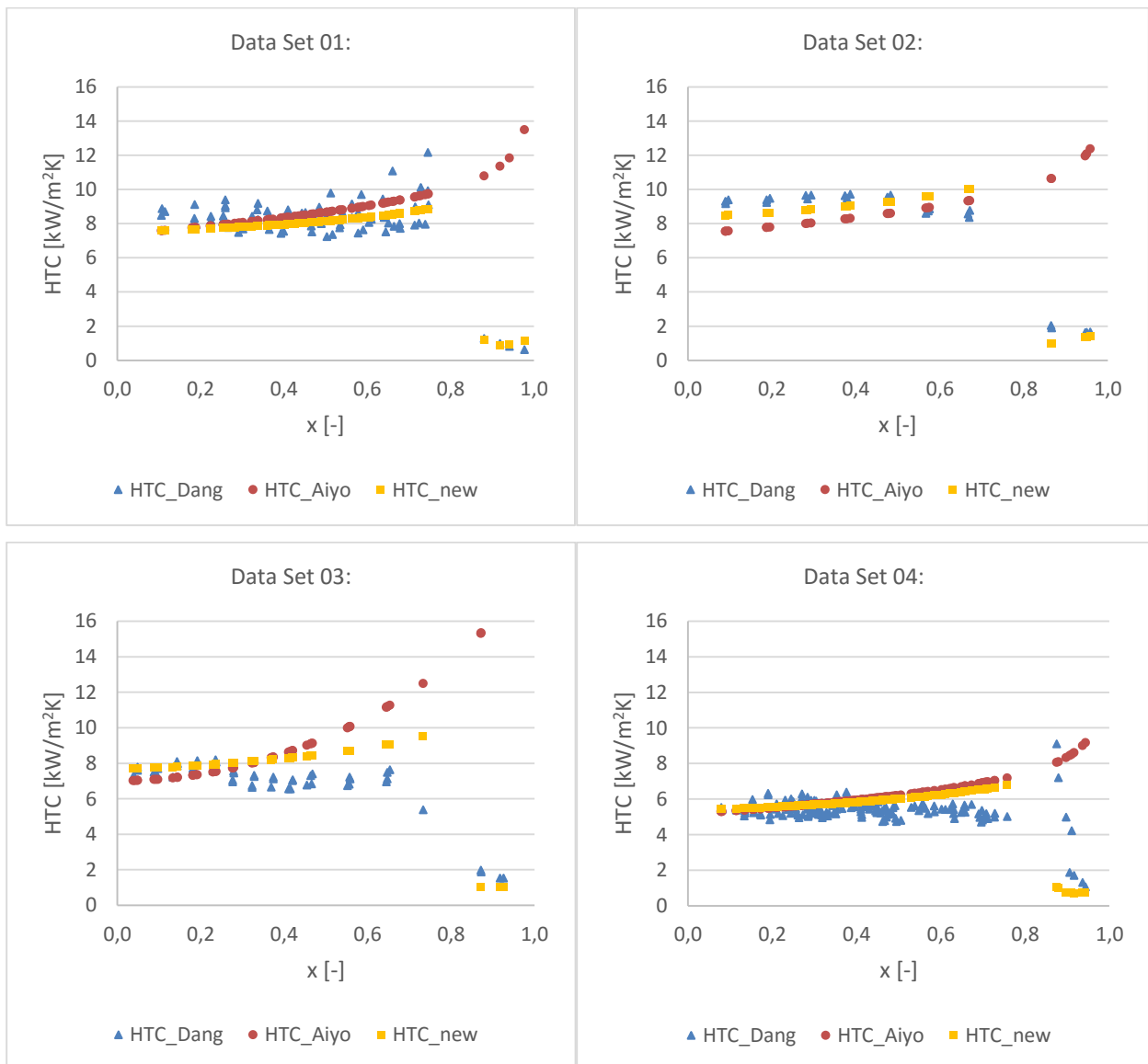
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MassFlux:	720	kgm-2s-1	
T_sat:	15	C	
Diameter:	2	mm	

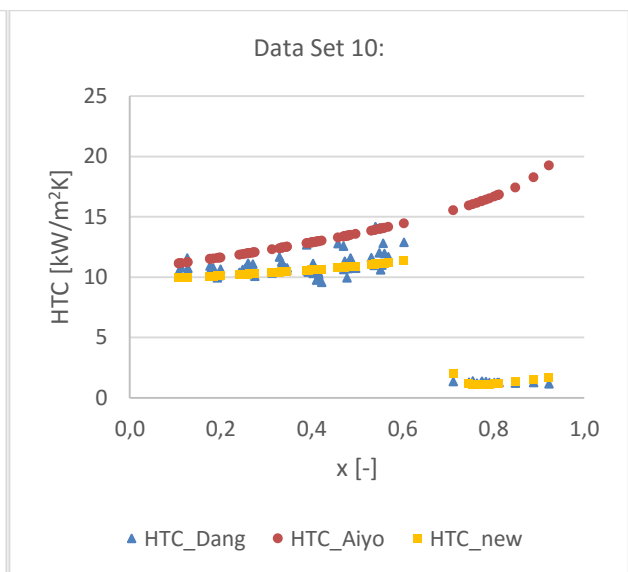
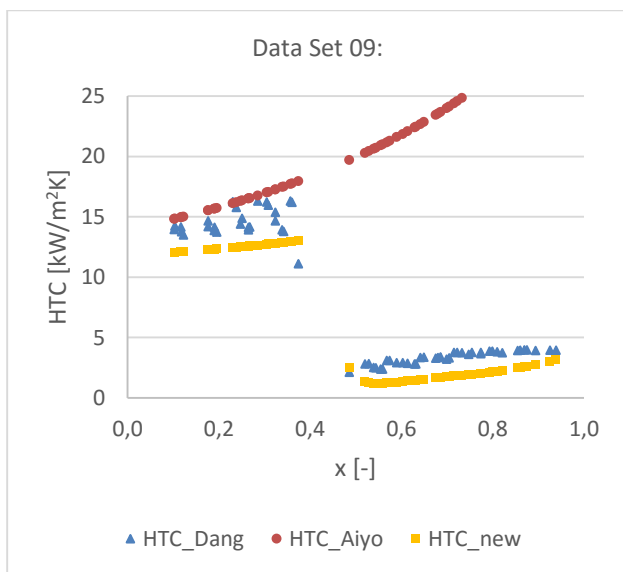
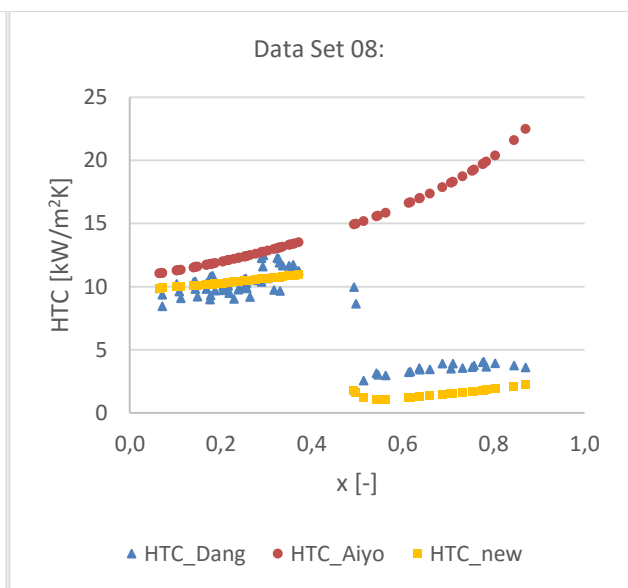
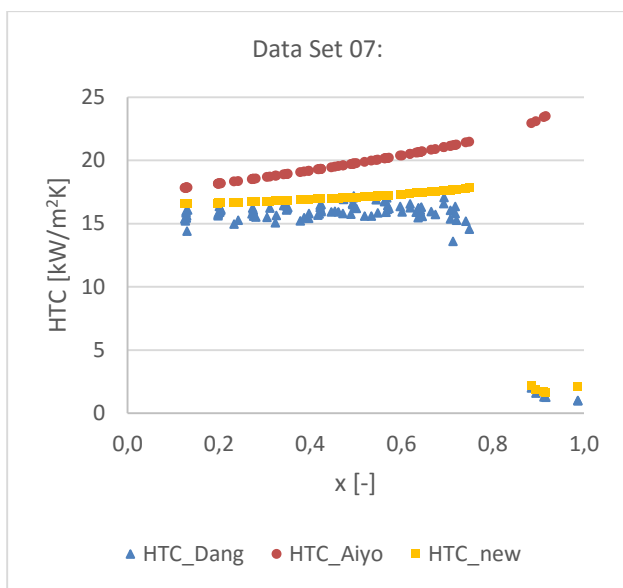
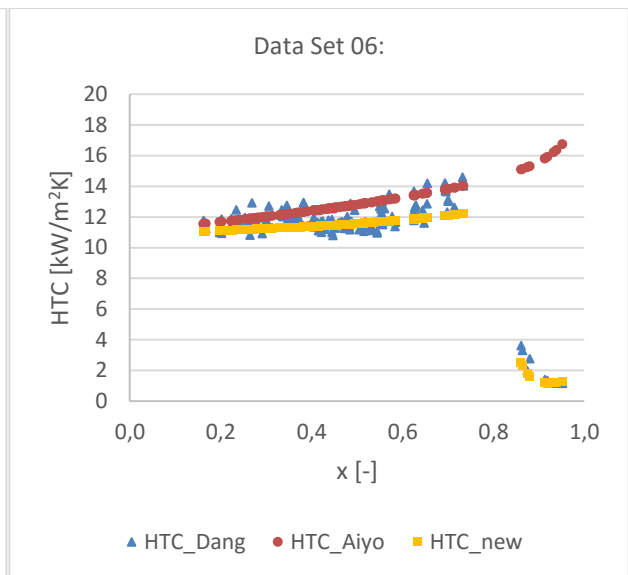
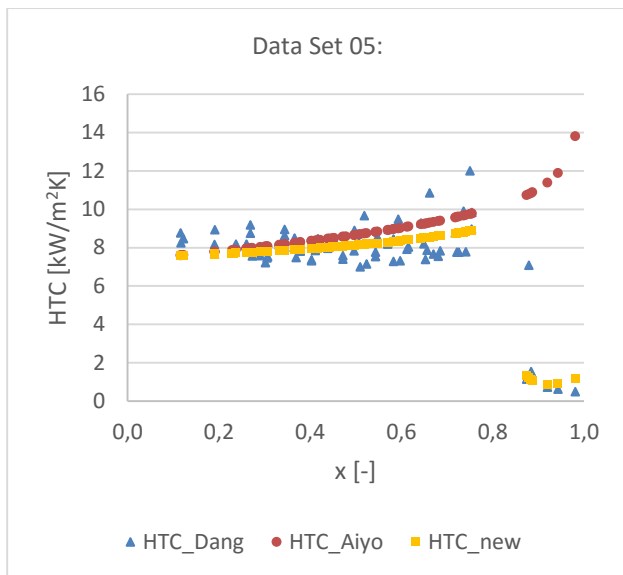
OCR's:		
OCR_exp:	1.0	%

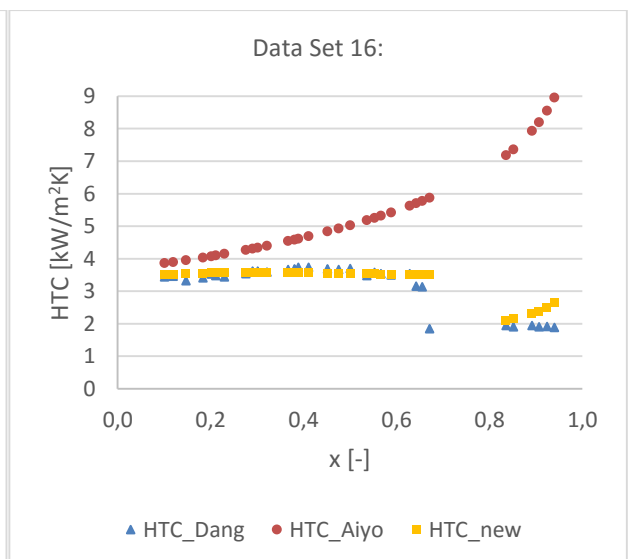
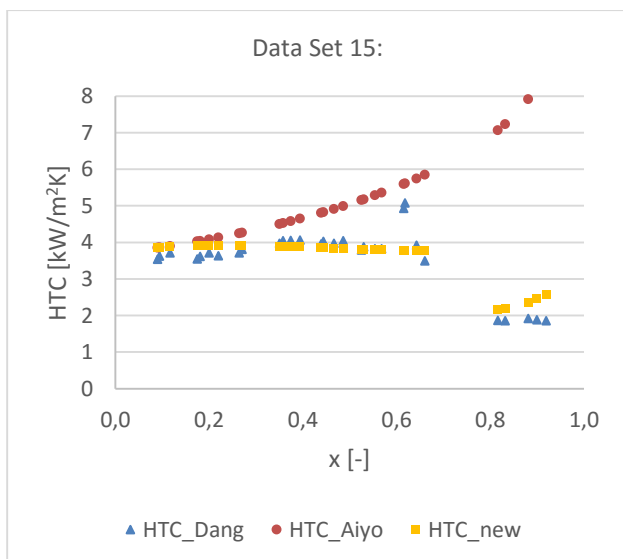
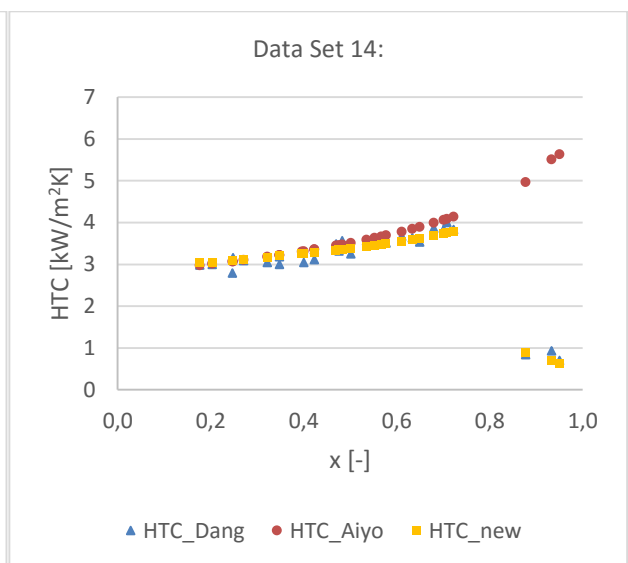
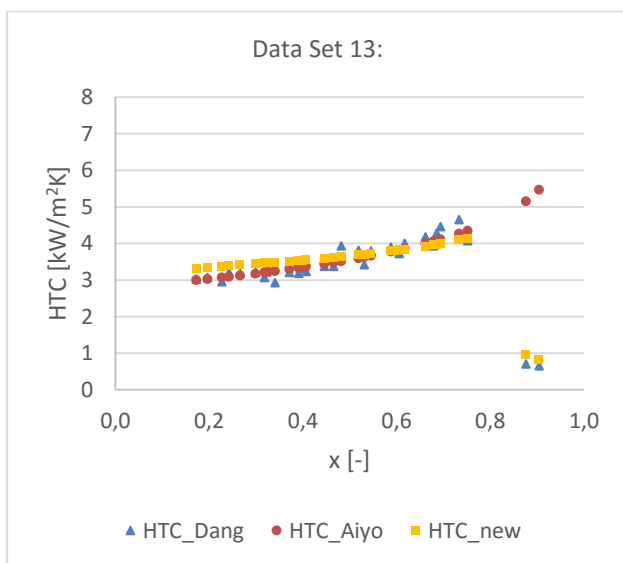
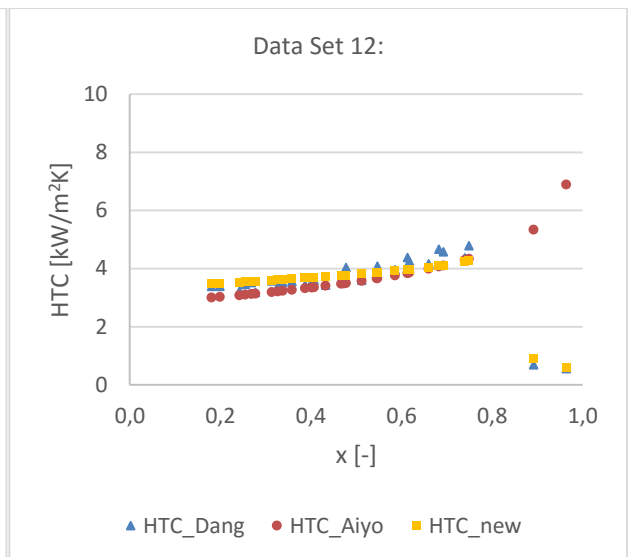
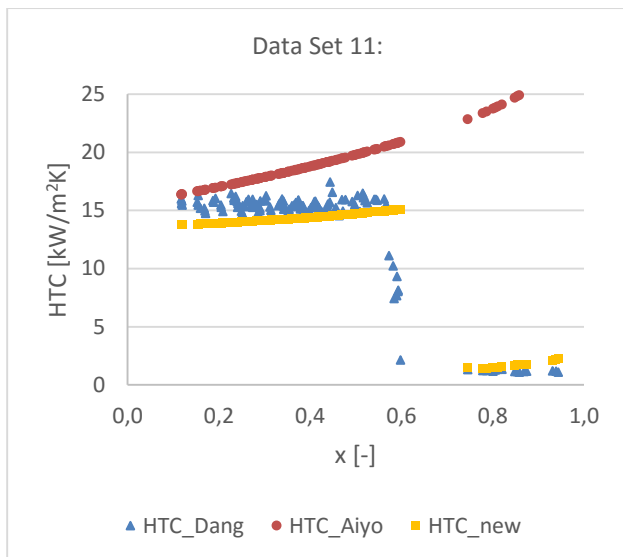
Data:			
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0.1741	6.38	5.766	5.513
0.2051	6.41	5.855	5.509
0.2086	6.15	5.866	5.508
0.2290	6.36	5.927	5.501
0.2389	6.08	5.958	5.497
0.2466	6.08	5.982	5.494
0.2593	6.45	6.022	5.487

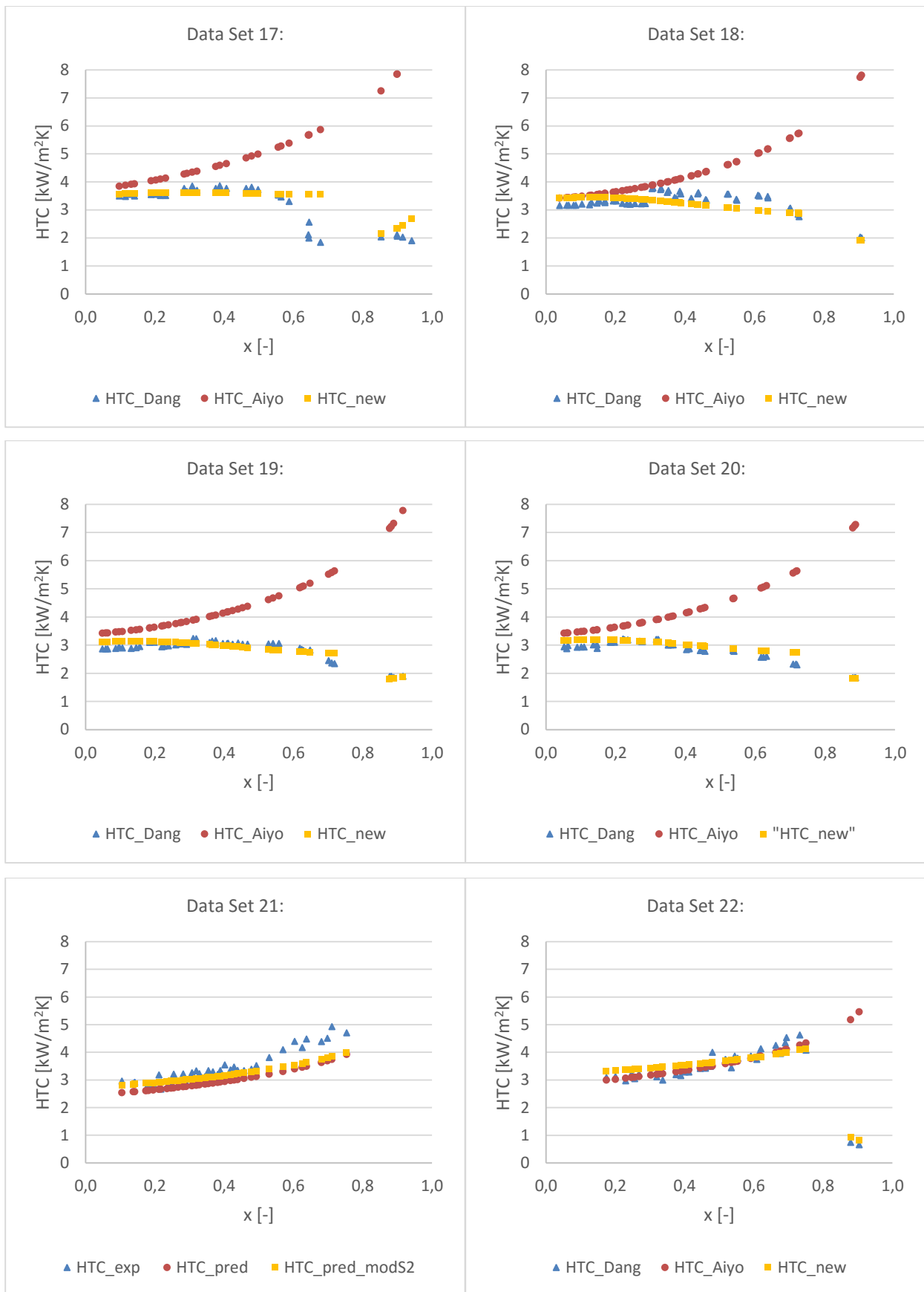
0.2635	6.04	6.036	5.485	0.4254	5.63	6.63	5.333	0.6404	1.52	7.706	2.24
0.2769	6.00	6.080	5.477	0.4387	5.80	6.685	5.317	0.6538	1.40	7.787	2.234
0.2818	5.95	6.096	5.474	0.4430	5.77	6.703	5.312	0.6756	1.40	7.923	2.224
0.2938	6.09	6.136	5.465	0.4542	5.63	6.752	5.298	0.6953	1.36	8.049	2.216
0.3001	5.99	6.158	5.46	0.4613	5.51	6.783	5.289	0.7128	1.67	8.165	2.209
0.3114	5.96	6.197	5.451	0.4746	5.61	6.842	5.272	0.7255	1.31	8.25	2.206
0.3212	5.96	6.231	5.443	0.4817	5.57	6.874	5.264	0.7438	1.68	8.376	2.201
0.3325	6.02	6.271	5.433	0.4908	5.50	6.915	5.252	0.7628	1.69	8.51	2.198
0.3353	5.90	6.282	5.431	0.4986	5.34	6.951	5.242	0.7846	1.39	8.668	2.198
0.3508	5.91	6.338	5.416	0.5126	5.41	7.018	5.225	0.7973	1.65	8.761	2.199
0.3529	5.82	6.346	5.414	0.5155	5.51	7.032	5.221	0.8142	1.41	8.889	2.203
0.3670	5.90	6.398	5.399	0.5274	5.39	7.09	5.206	0.8367	1.40	9.063	2.213
0.3705	5.96	6.412	5.396	0.5471	5.53	7.189	5.182	0.8543	1.46	9.202	2.227
0.3845	5.88	6.466	5.38	0.5507	4.96	7.207	5.177	0.8670	1.39	9.305	2.24
0.3902	5.75	6.488	5.374	0.5725	4.77	7.321	5.152	0.8881	1.48	9.478	2.273
0.4050	5.88	6.546	5.357	0.5848	1.72	7.388	5.138	0.9092	1.51	9.656	2.324
0.4085	5.84	6.561	5.353	0.6024	1.63	7.485	5.118	0.9394	1.49	9.918	2.456
0.4218	5.80	6.615	5.338	0.6242	1.48	7.61	2.249				

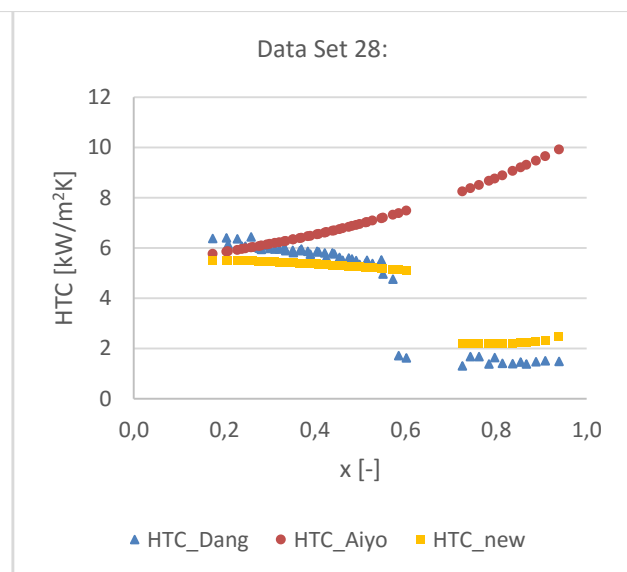
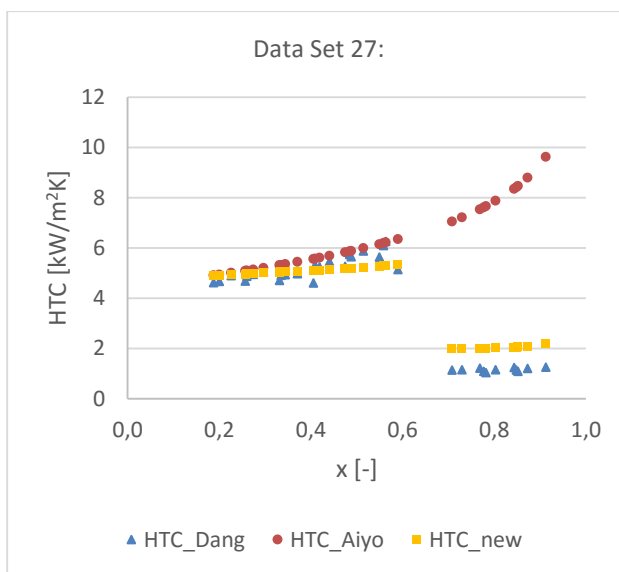
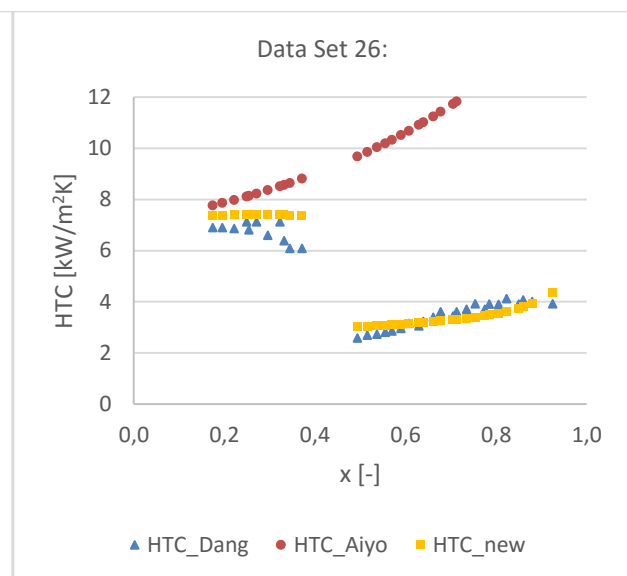
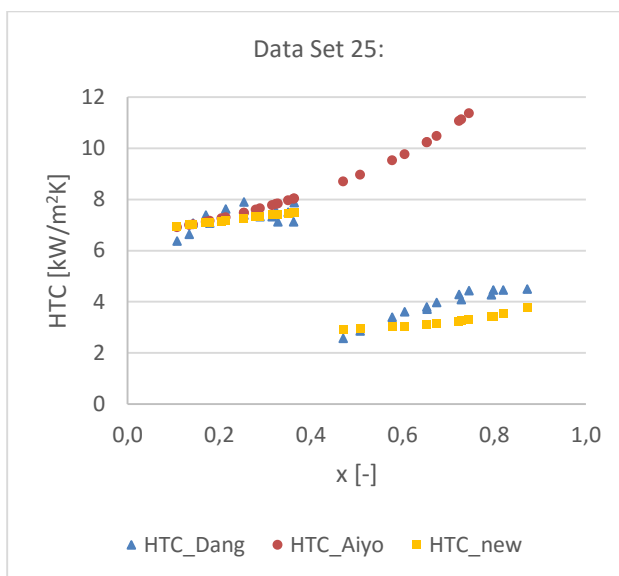
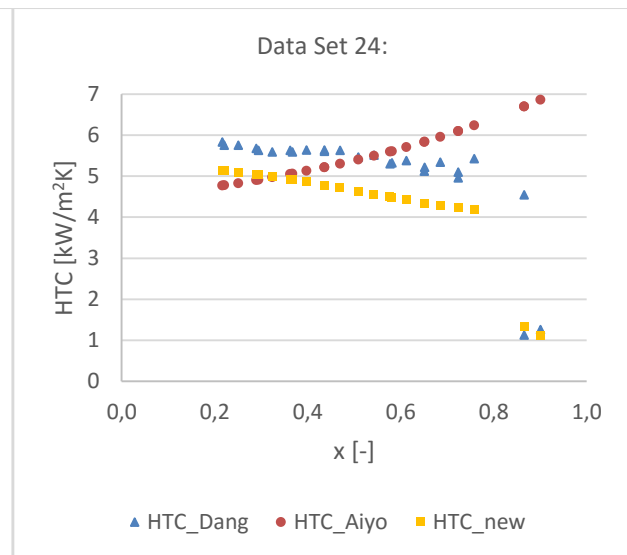
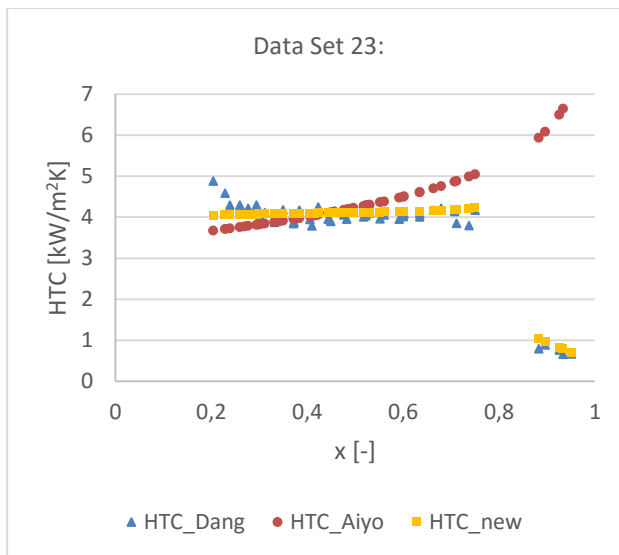
Graphical representation of data sets:











APPENDIX C: DRYOUT VAPOUR QUALITY DATA SETS

Dryout vapour quality data:

Data Set 01:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.84
Correlation data:	
Katsuta et al. (2008)	0.8437
New Correlation	0.7598

Data Set 06:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.81
Correlation data:	
Katsuta et al. (2008)	0.8139
New Correlation	0.7598

Data Set 11:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.57
Correlation data:	
Katsuta et al. (2008)	0.9327
New Correlation	0.6046

Data Set 02:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.77
Correlation data:	
Katsuta et al. (2008)	0.9584
New Correlation	0.6912

Data Set 07:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.81
Correlation data:	
Katsuta et al. (2008)	0.7852
New Correlation	0.7598

Data Set 12:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.76
Correlation data:	
Katsuta et al. (2008)	0.8437
New Correlation	0.7598

Data Set 03:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.73
Correlation data:	
Katsuta et al. (2008)	0.9536
New Correlation	0.7335

Data Set 08:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.46
Correlation data:	
Katsuta et al. (2008)	1.149
New Correlation	0.3828

Data Set 13:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.76
Correlation data:	
Katsuta et al. (2008)	0.8321
New Correlation	0.7598

Data Set 04:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.83
Correlation data:	
Katsuta et al. (2008)	0.8746
New Correlation	0.7598

Data Set 09:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.38
Correlation data:	
Katsuta et al. (2008)	1.108
New Correlation	0.3828

Data Set 14:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.77
Correlation data:	
Katsuta et al. (2008)	0.4216
New Correlation	0.7598

Data Set 05:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.84
Correlation data:	
Katsuta et al. (2008)	0.8437
New Correlation	0.7598

Data Set 10:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.63
Correlation data:	
Katsuta et al. (2008)	0.9668
New Correlation	0.6046

Data Set 15:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.66
Correlation data:	
Katsuta et al. (2008)	0.9453
New Correlation	0.6912

Data Set 16:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.66
Correlation data:	
Katsuta et al. (2008)	0.6728
New Correlation	0.6912

Data Set 21:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.76
Correlation data:	
Katsuta et al. (2008)	0.8626
New Correlation	0.7598

Data Set 26:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.38
Correlation data:	
Katsuta et al. (2008)	1.093
New Correlation	0.3828

Data Set 17:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.56
Correlation data:	
Katsuta et al. (2008)	0.4789
New Correlation	0.6912

Data Set 22:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.77
Correlation data:	
Katsuta et al. (2008)	0.8321
New Correlation	0.7598

Data Set 27:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.59
Correlation data:	
Katsuta et al. (2008)	0.9535
New Correlation	0.6046

Data Set 18:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.73
Correlation data:	
Katsuta et al. (2008)	0.9404
New Correlation	0.7335

Data Set 23:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.76
Correlation data:	
Katsuta et al. (2008)	0.8027
New Correlation	0.7598

Data Set 28:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.58
Correlation data:	
Katsuta et al. (2008)	0.9199
New Correlation	0.6046

Data Set 19:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.73
Correlation data:	
Katsuta et al. (2008)	0.6694
New Correlation	0.7335

Data Set 24:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.86
Correlation data:	
Katsuta et al. (2008)	0.7744
New Correlation	0.7598

Data Set 20:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.73
Correlation data:	
Katsuta et al. (2008)	0.4764
New Correlation	0.7335

Data Set 25:	
	Dryout vapour quality
Experimental data:	
Dang et al. (2013)	0.4
Correlation data:	
Katsuta et al. (2008)	1.133
New Correlation	0.3828

APPENDIX D: NEW FORMULA DEVELOPMENT DATA

New S factor data plot:

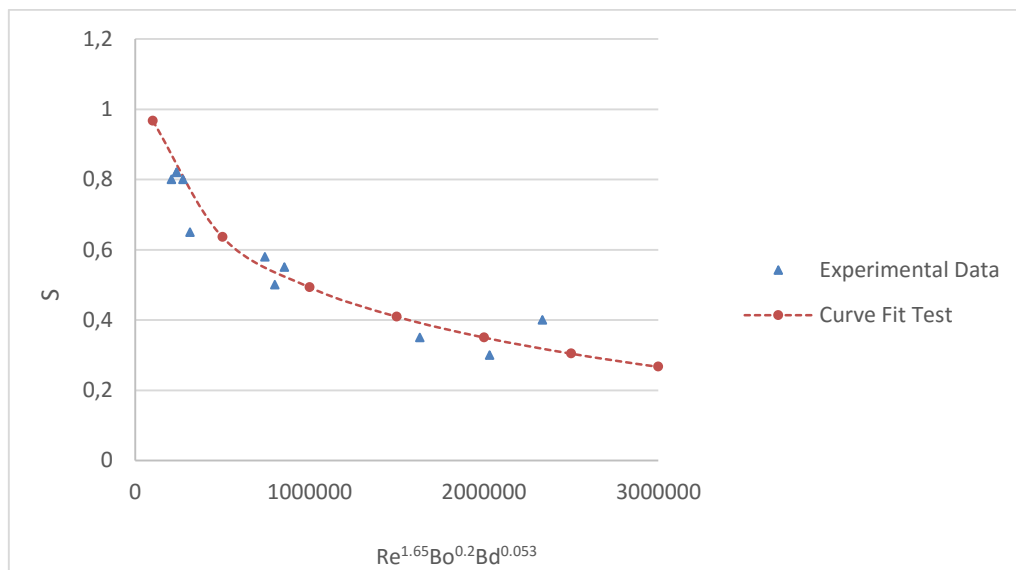


Figure D. 2: New S factor experimental data with predicted data overlay

Figure D.1 shows how the experimental data correlates with the S factor values predicted by equation (4.2). The red round markers with the broken line indicate the predicted values while the blue triangles show the experimental S factor values taken from the data of Dang et al. (2013).

New S_{oil} factor data plot:

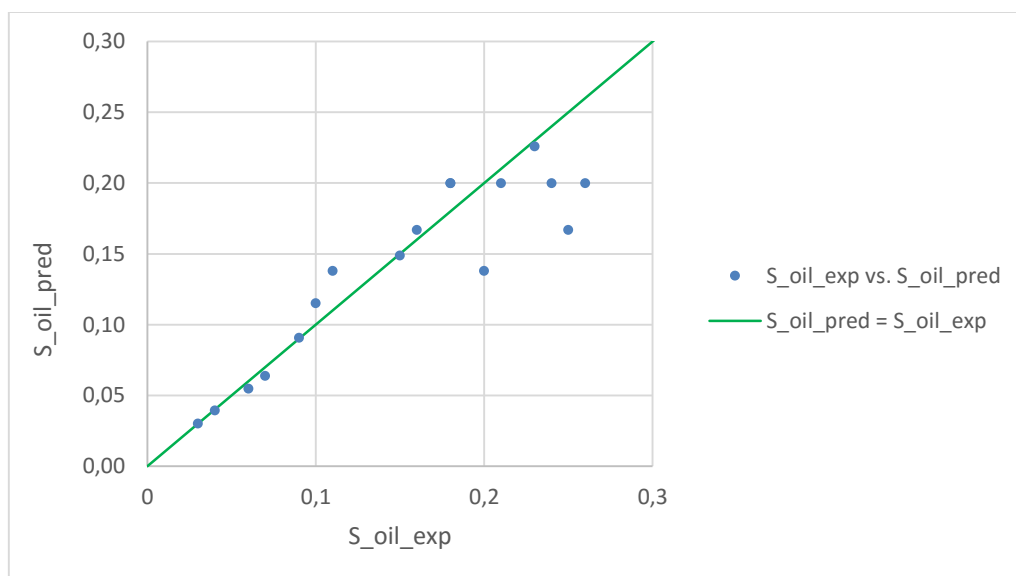


Figure D. 3: New S_{oil} factor experimental vs. predicted comparison plot

New S_{oil} factor data sets:

Table D. 1: New S_{oil} factor experimental and predicted data sets

Data set:	OCR	Exp. S_{oil}	Pred. S_{oil}	MAD	MRD
12	0.5	0.23	0.23	1.82%	1.82%
13	1	0.18	0.20	9.96%	-9.96%
14	5	0.15	0.15	0.87%	0.87%
15	1	0.1	0.12	13.11%	-13.11%
16	3	0.06	0.05	9.71%	9.71%
17	5	0.07	0.06	9.56%	9.56%
18	1	0.09	0.09	0.68%	-0.68%
19	3	0.03	0.03	0.72%	-0.72%
20	5	0.04	0.04	1.48%	1.48%
21	1	0.24	0.20	20.06%	20.06%
22	1	0.18	0.20	9.96%	-9.96%
23	1	0.21	0.20	5.05%	5.05%
24	1	0.26	0.20	30.06%	30.06%
25	1	0.2	0.14	45.07%	45.07%
26	1	0.11	0.14	20.21%	-20.21%
27	1	0.16	0.17	4.04%	-4.04%
28	1	0.25	0.17	49.93%	49.93%

Figure D.2 shows a direct comparison of the S_{oil} factors predicted by equation (4.5) and the corresponding experimental values from the data of Dang et al. (2013). Table D.1 shows a numerical comparison of the S_{oil} factors with OCR, MAD and MRD values for each data set.

Calculation condition (b) M factor data plot:

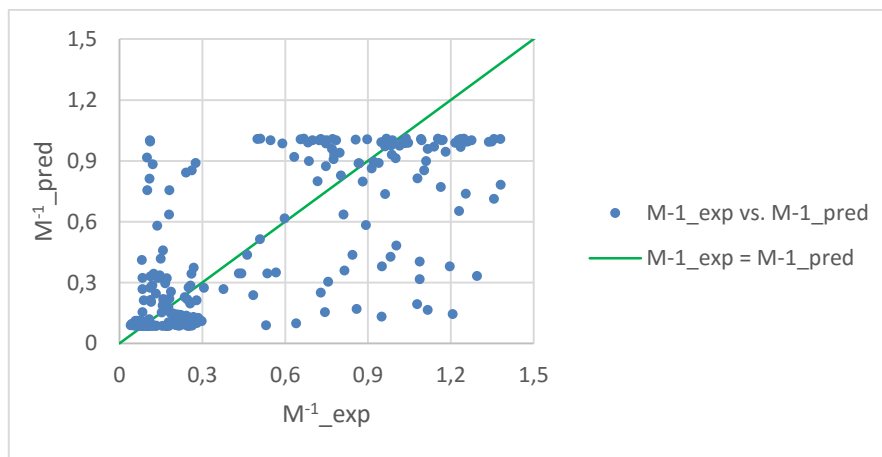


Figure D. 4: Calculation condition (b) M factor experimental vs. predicted data comparison plot

Calculation condition (c) M factor data plot:

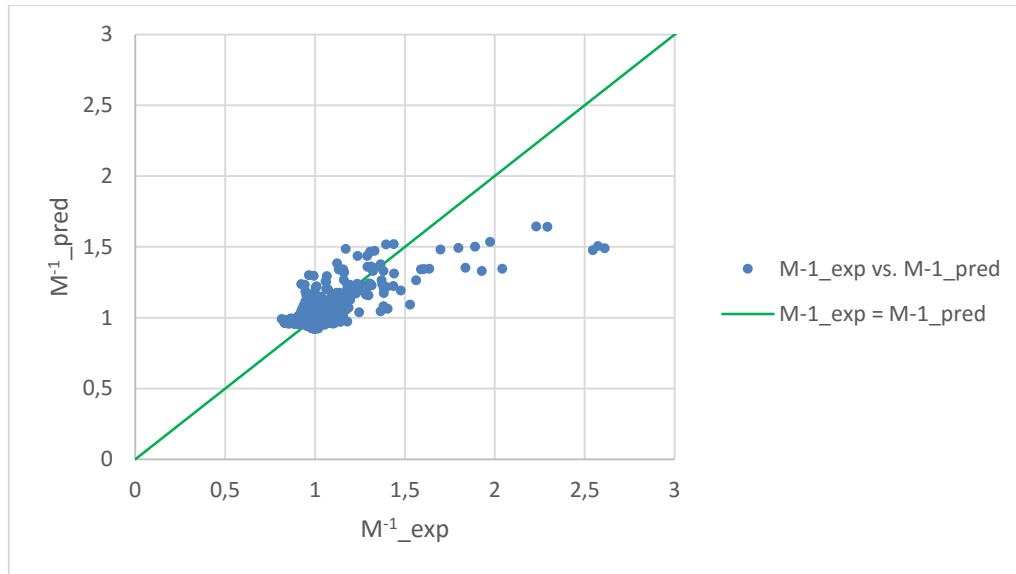


Figure D. 5: Calculation condition (c) M factor experimental vs. predicted data comparison plot

Calculation condition (d) M factor data plot:

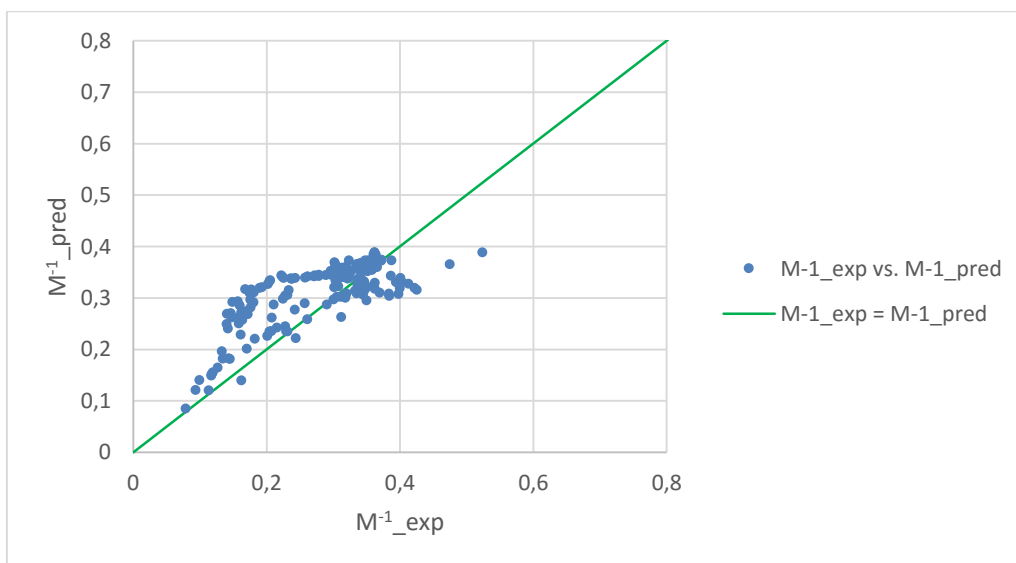


Figure D. 6: Calculation condition (d) M factor experimental vs. predicted data comparison plot

Figure D.3 to Figure D.5 show comparison plots for the experimental and predicted M factors for calculation conditions (b), (c) and (d) where the predicted values were obtained using equations (4.10), (4.7) and (4.12) respectively.

APPENDIX E: EQUATIONS OF NEW CORRELATION

For ease of reference all the relevant equations of the new correlation are listed here:

$$h_{tp} = \frac{Fh_{cb} + Sh_{nb}}{M}$$

$$h_{cb} = 0.023 \frac{k_l}{D} \left[\frac{G(1-x)D}{\mu_l} \right]^{0.8} Pr^{0.4}$$

$$h_{nb} = 207 \frac{k_l}{D_b} \left(\frac{qD_b}{k_l T_b} \right)^{0.745} \left(\frac{\rho_v}{\rho_l} \right)^{0.581} Pr_l^{0.533}$$

$$F = 0.8 + 0.5 \left(\frac{1}{X_{tt}} \right)^{1.2}$$

$$D_b = 0.51 \left[\frac{2\sigma}{g(\rho_l - \rho_v)} \right]^{0.5}$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.1}$$

$$S = S_{oil} \left(-0.206 \ln(Re^{1.65} Bo^{0.2} Bd^{0.053}) + 3.55 \left(\frac{D}{D_{ref}} \right)^{0.0675} \right)$$

$$S_{oil} = 1 ; OCR = 0$$

$$S_{oil} = 0.0087(OCR)^2 - 0.065(OCR) + 0.215 \left[0.675 \left(\frac{D}{D_{ref}} \right)^{-0.38} \left(\frac{G}{G_{ref}} \right)^{-0.2} \right] ; OCR > 0$$

where: $D_{ref} = 2 \text{ [mm]}$

$$G_{ref} = 720 \text{ [kg / m}^2\text{s]}$$

$$x_{dryout} = 0.9549 \times e^{-1.45 \times 10^{-5} (D_{ref}/D)^{1.5} Re_{avg}}$$

For $x < x_{dryout}$ and $OCR = 0$:

$$M = 1$$

For $x > x_{dryout}$ and $OCR = 0$:

$$M = \frac{1}{\left(e^{-200x_{corrected}^2} + 0.2x_{corrected}^{0.5} \right)}$$

where:

$$x_{corrected} = x - x_{dryout}$$

For $x < x_{dryout}$ and $OCR > 0$:

$$M = a + bx^2$$

where:

$$a = -0.0043ReBo + 0.9535$$

$$b = 0.1851ReBo - 0.0483$$

For $x > x_{dryout}$ and $OCR > 0$:

$$M = \frac{1}{\left[(slope)(x_{corrected}) + intercept \right]}$$

where:

$$slope = -19 + \left(-6.3 \times 10^{-5} \right) Re + 2 \ln(Re) + 0.15$$

$$intercept = 0.79 + \frac{-4.4}{\ln(Re)}$$

APPENDIX F: EXPERIMENTAL SETUP / UNCERTAINTY ANALYSIS

The experimental setup used in the study by Dang et al. (2013) is illustrated in this section. The setup was used to generate the experimental data of the study by Dang which is also used in this study. A test section containing a generic heat exchanger tube can be seen in the schematic diagram of Figure F.1 and a detailed view of the test section is shown in Figure F.2. For a full description and explanation of the experimental setup and the test procedure, please refer to the study by Dang et al. (2013). It is however important to mention here that this study subdivided the test section shown in Figure F.2 into equal vapour quality control volume increments in order to perform the necessary calculations contained in the EES code shown in Appendix A.

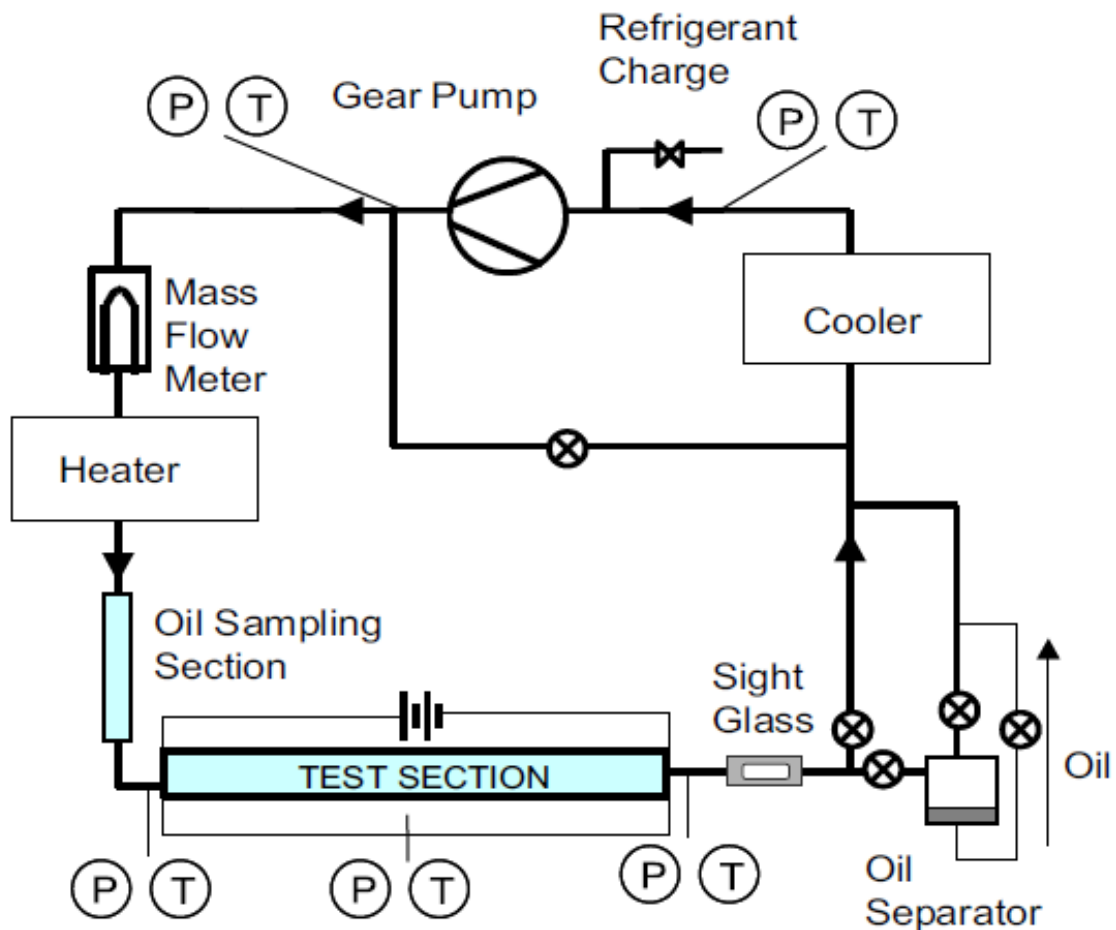


Figure F. 1: Schematic diagram of experimental apparatus used in the study by Dang (Dang, et al., 2013)

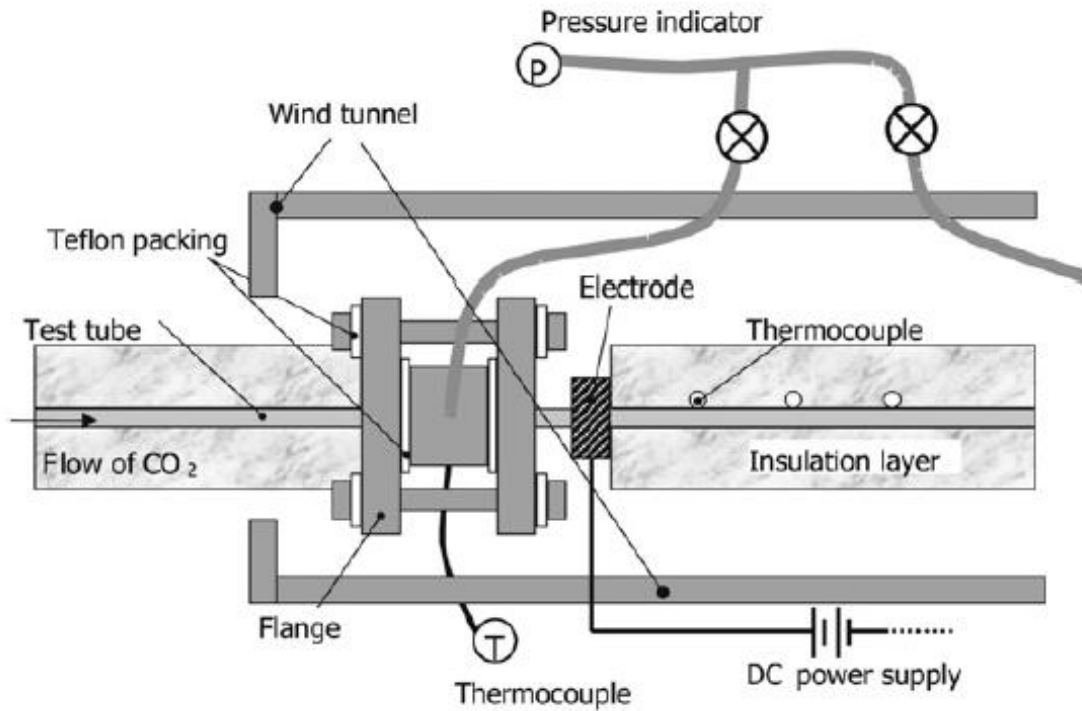


Figure F. 2: Detailed structure of test section used in experimental apparatus of Dang (Dang, et al., 2013)

Various parameters and values for these parameters used in the study by Dang et al. (2013) to generate the test results are shown in Table F.1. A constant test section tube length of 2 [m] was specified in the EES code used for calculations in this study as is shown in Appendix A, the value for which was obtained from the study by Dang et al. (2013). The experimental results from the study of Dang for all test conditions are shown in Appendix B along with the calculated results by the correlations of Aiyoshizawa and the correlation developed in this study. The EES programs of Appendix A were used to obtain these calculated results.

Table F. 2: Experimental conditions of study by Dang also used for this study (Dang, et al., 2013)

Tube material	SUS316
Inner diameter of tube [mm]	2, 4, 6
Oil type	PAG100
Oil concentration [wt%]	0.5–5.0
Mass velocity [$\text{kg m}^{-2} \text{s}^{-1}$]	360, 720, 1440
Heat flux [kW m^{-2}]	4.5, 9, 18, 36
Evaporation temperature [$^{\circ}\text{C}$]	15
Quality	0.1–1.0

Table F. 2: Measuring device uncertainty in the study by Dang (Dang, et al., 2013)

Variable	Device	Range	Accuracy
Temperature of tube wall	Thermocouples	0–50 °C	±0.1 K
Temperature of refrigerant	Pt 100	–50–200 °C	±0.03 K
Mass flow rate	Coriolis type flow meter	0–150 g min ^{–1}	±0.5% reading value
Pressure	pressure sensor	1–20 MPa	±0.1% full scale
Voltage	Voltmeter	0–64 V	±0.02% reading value
Inner diameter			±0.03 mm ^a
Length	Ruler	0–6 m	±0.001 m
a Provided by the manufacture.			