CHAPTER 2

LITERATURE REVIEW

The initial step in the understanding of the damage experienced by the column-top condensers and the dimple plate heat exchangers in general is to determine the characteristics of the most destructive flow-induced vibration mechanisms. For this reason the scientific literature was consulted.

According to numerous authors the two most destructive flow-induced vibration mechanisms are fluid-elastic instability and periodic wake shedding. The other mechanisms that are normally investigated include periodic vortex shedding (flow periodicity), multi-phase buffeting, acoustic resonance and turbulence buffeting.

If a structure had been exposed to a variable flow velocity of a medium, each of these mechanisms could be seen at a certain range of frequencies. If these different mechanisms were compared in terms of the amplitude of vibration, the most severe mechanisms could be identified as fluid-elastic instability and periodic wake shedding. (Goyder, 2002; Pettigrew & Taylor, 2003; Paidoussis, 2006).

Each of these excitation mechanisms will be studied briefly, as the scope of the dissertation is based on the control of the vibrations and not on the excitation mechanisms themselves. Only certain important features of the excitation mechanisms will be studied to determine which type of excitation mechanism is present.

2.1. Fluid-elastic instability

Fluid-elastic instability is caused when a positive feedback loop is created between the movement of the structure and the flow of the fluid. The motion of the structure extracts energy from the fluid flow that must be dissipated by the damping of the system. At sufficiently large velocities, the energy that is extracted from the fluid is more than the energy that can be dissipated; therefore the amplitude of vibration increases. Once fluid-elastic instability has been initiated, the amplitude of the vibrations is only limited by the structure clashing with mountings or other internal structures, or by the yielding of the structure itself (Blevins, 2002).

Fluid-elastic instability has the important characteristic that there is a significant increase in the vibrational amplitude once fluid-elastic instability has been initiated and the velocity of flow is increased further. This threshold where fluid-elastic instability starts, is often called the critical flow velocity(Goyder, 2002).

The onset of fluid-elastic instability can be avoided by keeping the fluid velocity below the critical flow velocity. Due to the fact that the flow velocity is fixed by the process conditions, the critical flow velocity itself must be manipulated (Goyder, 2002).

The most common way of increasing the critical flow velocity is to increase the natural frequency of the structure by making the structure stiffer(Blevins, 2002).

If fluid-elastic instability still remains a problem after the structure has been stiffened as much as practicably possible, the introduction of damping into the system increases the amount of energy dissipated and, thereby increasing the flow velocity where instability occurs(Goyder, 2002).

The manufacturers of the dimple plate heat exchangers use the cross-linking of the plate pack to stiffen the core of the heat exchangers. This method is used especially in large heat exchangers (low stiffness), which will be exposed to high flow velocities (> critical flow velocity).

2.2. Periodic vortex shedding

The case of the dimple plate heat exchangers provides a very interesting case of periodic vortex shedding due to the complexity of the structure subjected to the flow. The structure does not only experience the normal forces due to the structures (panels) shedding vortices behind it, but the surface of the panels, being dimpled, creates additional forces due to the ejection of vortices from the dimples themselves.

As the dimple plate technology is still relatively new in industrial application and in limited use, the combination of the two types of fluid-induced vibration has not been studied. These two different mechanisms have, however, been studied individually and the different studies will be summarised independently.

2.2.1. Vortex shedding of panels

The flow wake behind all bluff bodies oscillate with a frequency proportional to the flow velocity, due to the shedding of vorticity from the stagnant region in the wake behind a body. The oscillating wake gives rise to a time-dependant force on the structure. Though vortex shedding always occurs, it only results in large vibration amplitudes if the vortex shedding frequency equals the natural frequency of the structure, however (Goyder, 2002).

The vortex shedding frequency also has the feature that in certain cases the coincidence between the vortex shedding frequency and the natural frequency does not have to be exact. The flow causes small movements at the natural frequency of the structure. This motion of the structure alters the vortex shedding frequency and brings it closer to the natural frequency of the structure.

This effect causes the vortex shedding frequency to “lock-in” or “lock-on” to the natural frequency of the structure. The lock-in phenomenon never achieves such a large amplitude that catastrophic failure occurs, as the vibration is self-limiting in the order of the thickness of the body, while the increased amplitude increases the stress on the structure, causing fatigue after a period of time.(Crawley, Curtiss, Peters, Scanlan, & Sisto, 1995).

Due to the “lock-on” feature of vortex shedding vibration, designers usually try to keep the natural frequency of the structure (f_n) out of the range where “lock-on” is likely to take place with the shedding frequency (f_s) (Goyder, 2002).

$$0.8 \cdot f_n < f_s < 1.2 \cdot f_n \tag{2.1}$$

Sahin *et al.* (2006) used the particle image velocimetry (PIV) technique to obtain the phase averaged turbulent flow characteristics in a heat exchanger flow passage. They used a model of a single cylinder between two plates to study finned tube heat exchangers. By using FFT analysis on the results it was indicated that the vortex shedding frequency is the dominant frequency of all the turbulent vortices(Sahin, Akkoca, Ozturk, & Akilli, 2006).

Lam, *et al.* (2004) made an experimental investigation on the fluctuating forces in varicose cylinders in cross flow, caused by vortex shedding. In the study certain characteristics of vortex induced vibrations can be seen.

By changing the velocity of the fluid, the Reynolds number and, therefore, the vortex shedding frequency was altered. By using this method, the measured response of the system was recorded for a range of fluid-induced forcing frequencies.

From the results it can be seen that, although the vortex shedding frequency is always evident, it only leads to large amplitudes when it combines with a natural frequency. The “lock-in” phenomenon was also identified experimentally(Lam, Wang, & So, 2004).

2.2.2. Vortex ejection from dimples

Unlike vortex shedding, which occurs with all bluff bodies subjected to flow velocity, vortex ejection is a mechanism that is confined to structures with dimpled surfaces. This mechanism provides the heat transfer augmentation mentioned previously and has been researched in detail.

A number of studies on the flow structure and heat transfer of dimpled channels were conducted at the University of Utah under Ligrani, Mahmood, Harrison, Clayton, Nelson, Won and Zhang and reported from 2001 to 2005. In all the studies horizontal smoke lines were used to visualise the flow by illuminating the smoke with a thin sheet of light. By recording a series of concurrent images over a short time, the time-varying instantaneous flow at a specific section could be visualised

(Ligrani, Mahmood, Harrison, Clayton, & Nelson, 2001; Ligrani, Harrison, Mahmood, & Hill, 2001; Mahmood & Ligrani, 2002; Won, Zhang, & Ligrani, 2005).

The authors of these studies tried to understand the mechanism of vortex ejection from the dimples by determining the general form, transient characteristics and the resulting vortex ejection frequency.

To take it further, the effect of changing the dimple and channel geometry on these characteristics was also studied. By discussing the results of the different studies in this order, a better understanding of vortex ejection can be obtained.

2.2.2.1. *General form of vortices*

Ligrani, Mahmood *et al.* (2001) studied the effect of protrusions and dimples on the local flow structure in a channel (Ligrani, Mahmood, Harrison, Clayton, & Nelson, 2001). By photographing the flow patterns over a dimpled wall, with the opposite wall smooth, the general characteristics of the flow structure over any dimpled surface could be seen.

The results of this study indicated that above the dimples three vortex pairs could be identified by “mushroom-shaped” smoke patterns. Between the vortex pairs a distinct up-wash region was visible. The most prominent up-wash region and the primary vortex pair were located directly above the centre of the dimple and range through the whole channel height. Two other secondary vortex pairs were located above the left and right edges of the dimple and only spanned half the height of the channel(Ligrani, Mahmood, Harrison, Clayton, & Nelson, 2001).

2.2.2.2. *Transient flow*

Ligrani, Harrison, *et al.* (2001) aimed to give a more complete picture of the instantaneous flow than the previous studies and described the periodical ejection of vortices from the dimples (Ligrani, Harrison, Mahmood, & Hill, 2001).

They described a periodical process of fluid ingress into a dimple and ejection of vortices from the dimple. The ejection of the vortices necessitated the inrush of fresh fluid, causing the repeat of the process at a fixed frequency, as long as the flow condition remained constant over the dimple. The ejected vortices were seen to synchronise the processes over all the dimples by, when travelling downstream after ejection, promoting the inrush of fluid into subsequent dimples.

2.2.2.3. *Vortex ejection frequency*

The periodic process of vortex ejection happens at a frequency determined by the geometry of the dimples and the flow conditions, due to the fact that the turbulence that is generated continues to interact periodically with the rest of the structure after ejection from the dimple. This effect causes turbulent buffeting to be generated downstream of the dimple, creating “noise” in the frequency spectrum.

Won, Zhang, *et al.* (2005) used an ensemble-averaged power spectral analysis to determine the flow energy levels at particular frequencies due to coherent organised motion caused by the vortex ejection (Won, Zhang, & Ligrani, 2005). This spectrum, therefore, provided the energy available to excite vibration at specific frequencies.

From the results it was found that there was a variation in frequency of the excitation between the primary and secondary vortices. A further variation in frequency, due to the location of the dimple on the test section, was evident. When these vortices interacted with the structure downstream, further turbulent noise was generated.

This study shows that the characteristic of the vortex ejection mechanisms would not be a pronounced peak, but rather a band of peaks, together with an amount of turbulent noise.

The frequency of the vortex ejection excitation was between 7.3 Hz and 4.9 Hz, and had a general tendency to decrease with an increase in Reynolds number.

2.2.2.4. *Effect of changing aspect ratio*

The aspect ratio for the dimpled section (D/H) is the non-dimensional measure for the height of the channel and is defined as the ratio of the height of the channel (H) to the diameter of the individual dimples (D). The height of the channel is measured from the flat surface between the dimples and the top surface (see Figure 13).

Mahmood and Ligrani (2002) studied the case of varying aspect ratios in dimpled plate test sections and described that all the general characteristics described in the previous sections, were evident in all the sections with different aspect ratios (Mahmood & Ligrani, 2002).

The effect of the reduction in aspect ratio was described in more detail by Ligrani, Harrison, and others by varying the aspect ratio and determining the frequency of primary vortex shedding (Ligrani, Harrison, Mahmood, & Hill, 2001).

It was generally concluded that the ejection frequency seemed to reduce with the reduction aspect ratio, but the effect of the decrease in aspect ratio on the Reynolds number complicated the results. The frequency of primary vortex shedding was found to be between 4.3 and 11 Hz.

The decrease in aspect ratio was also observed to increase the intensity of the vortices. The secondary vortex pair also increased in strength relative to the primary vortex pair.

2.2.2.5. *Stream-wise development*

The characteristics of the vortices were also found to be dependent on the location of the dimple relative to the other dimples. The fact that the upwind vortices encouraged the inrush of fluid into the downstream vortices, the more a dimple is located downstream, the more intense the vortices that were ejected (Ligrani, Harrison, Mahmood, & Hill, 2001).

2.2.2.6. *Effect of dimple depth*

Won, *et al.* (2005) used the same techniques to study the effect of dimple depth on the flow structure above dimpled surfaces. The depth of the dimples were given by the non-dimensional quantity δ / D, where δ is the depth of the dimple and D is the print diameter.

The results of the study showed that the depth of the dimples did not influence the frequency of vortex ejection significantly, while deeper dimples ejected stronger primary vortex pairs and created larger and stronger secondary vortex pairs.

2.3. Conclusion

The two most destructive mechanisms of fluid-induced vibration are fluid-elastic instability and periodic vortex shedding. Although fluid-elastic instability is very destructive, it is relatively easy to avoid by making the structure as stiff as possible.

Periodic vortex shedding occurs in two distinct ways on a dimpled structure, such as the panels of the dimpled plate heat exchanger, namely vortex shedding behind the body and vortex ejection from the dimples.

The basic vortex shedding mechanism is caused by the shedding of vortices behind the bluff body (panel). This type of vibration causes large vibration amplitudes when the frequency of vortex shedding comes close to the natural frequency of the structure. There is also the added characteristic that it can lock on to a certain natural frequency, causing large vibrations, without being exactly equal to the natural frequency ("lock in"). The vortex shedding frequency increases with the increase of the flow velocity.

Flow over a dimple in a channel generates transient vortices that are ejected at a fixed frequency. Primary vortices are ejected from the centre of the dimple and smaller secondary vortices from the sides of the dimple. Small variations in the frequency of ejection are evident between primary and secondary vortices and dimples in the centre of the test section and dimples on the sides of the test section. The ejection frequency is decreased with an increase in the Reynolds number or the decrease of the channel.

The intensity of the vortices can be increased by decreasing the aspect ratio or increasing the depth of the dimples on the panels. The intensity of the vortices further increases naturally with the distance covered downstream over the dimpled panel.

Although both these vibration mechanisms have been studied separately by numerous authors, the combined effects of the two mechanisms are largely unknown. The combined effects will, therefore, have to be experimentally evaluated to determine the actual characteristics of the vibration.