Chapter 5

Comparison of results

5.1 Introduction

In Chapter 2 a number of HTRI analyses were done to determine at which mass flow rates the ES 208 Tail gas heat exchanger may experience vibration. CFD analyses were done in Chapter 3 to determine the pressure drop and cross-flow velocity distributions through the heat exchanger to compare with the values obtained from the HTRI results. The results of the vibration measurements are described in Chapter 4 and Appendix E. In this chapter, the results of the previous three chapters will be compared to determine the accuracy of the HTRI predictions, as well as the margins of uncertainty associated with these predictions.

5.2 Comparison of pressure drop values through the heat exchanger

In Chapter 3 (figure 3.11 repeated as figure 5.1) the HTRI and CFD pressure drop values per meter were compared. This was done to calculate the mass flow rate through the heat exchanger for the measured results. At lower mass flow

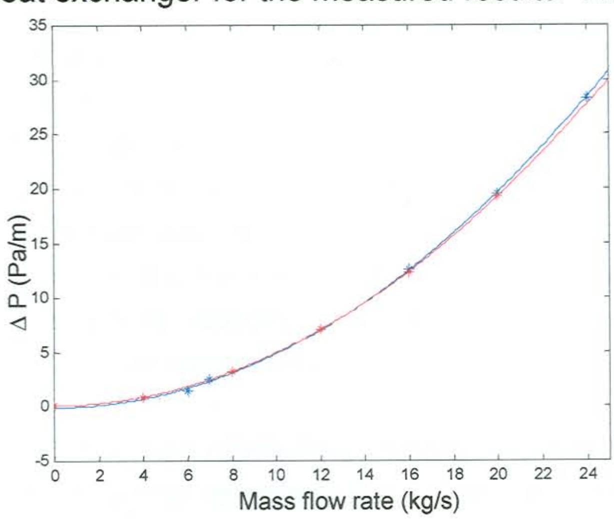


Figure 5.1: Pressure drop per meter through heat exchanger (blue – CFD results, red – HTRI results)

rates the pressure drop values for the two methods are the same, but at higher mass flow rates the CFD pressure drop value is slightly higher than the HTRI value. This is due to the limitations in the number of cells used for the CFD analyses as described in Section 3.2 and Appendix C.

5.3 Excitation frequencies and critical velocity.

The CFD analyses calculated the flow velocities and pressure distributions inside the heat exchanger. To determine the excitation frequencies, these velocity values obtained from the analyses can be substituted into equations 1.15 to 1.18. In Section 5.3.1 to 5.3.3 the CFD calculated average cross-flow velocities (Chapter 3) are compared to the HTRI calculated values (Chapter 2). The excitation frequencies associated with these average cross-velocities are compared to the measurements from Chapter 4 in Section 5.3.4.

5.3.1 Vortex shedding average cross-flow velocity

In Chapter 2 the HTRI analysis used the average cross-flow velocity to calculate the excitation frequency values. HTRI uses one average velocity value for a specific mass flow rate, and that particular velocity was compared to the velocities calculated with the CFD analyses. The problem with the CFD velocities is that due to the flow patterns through the heat exchanger, a different average cross-flow velocity is obtained at each cell.

If the cell velocity values at a specified plane between two baffles are averaged, as was done in Chapter 3, the cross-flow velocities between the different baffles can be represented by a single equation (red line in figure 5.2). This equation is a function of the position of the plane from the centre of the heat exchanger, as well as the mass flow rate (as described is Chapter 3 and Appendix C). The HTRI analyses only calculated the lowest natural frequency of the tube, therefore only the average cross-flow velocity associated with excitation at the lowest natural frequency of the tube was compared.

In figure 5.2 the HTRI average cross-flow velocity and baffle tip velocity, as well as the CFD average cross-flow velocity in the y-direction is shown.

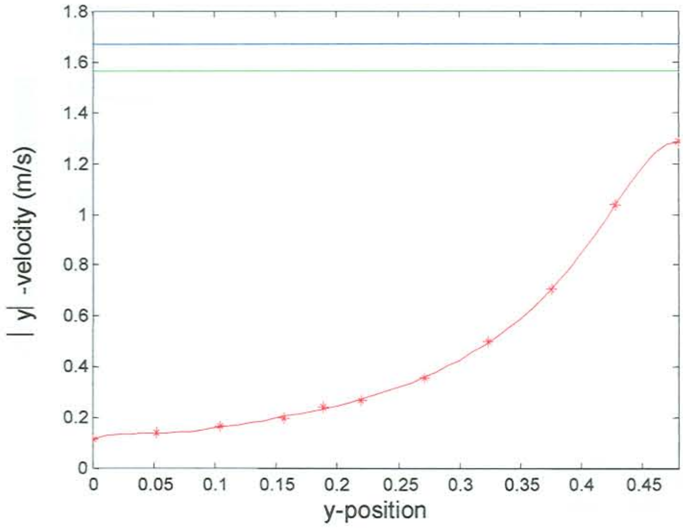


Figure 5.2: Cross-flow velocity between baffle type 1 and 2 (at inlet section) in the y-direction for a mass flow rate of 8 kg/s.
(red – CFD results, blue – HTRI average cross-flow velocity, green – HTRI baffle tip velocity)

In the section directly underneath the inlet of the heat exchanger (figure 5.2), the flow is mainly in the y-direction, but in figure 5.3 the cross-flow velocity in the x-direction was taken into account and slightly more accurate results were obtained.

Figures 5.2 and 5.3 both indicate that the maximum average cross-flow velocity is at the inlet opening of the shell (at y=0.5). This maximum value compares fairly well with the predicted HTRI cross-flow velocity and baffles tip velocity, although HTRI predicted an average cross-flow velocity value that is 20 percent higher than the maximum CFD value.

The tubes below the inlet nozzle of the heat exchanger are only supported at every third baffle (figure 2.2). These tubes are more likely to vibrate, because their natural frequency of 28.56 Hz will match the excitation frequency due to vortex shedding. The CFD average cross-flow velocity in figure 5.3 is only for the tube section between baffle type 1 and 2. The velocities between baffle type 2 and 3, and type 3 and 1 also need to be taken into account.

Figures 5.4 and 5.5 show the velocities between baffle type 2 and 3, and 3 and 1 together with the HTRI predicted velocities. The CFD calculated velocity values are considerably lower than at the section directly below the inlet (between baffle type 1 and 2) as well as the HTRI average cross-flow velocity and baffle tip velocity.

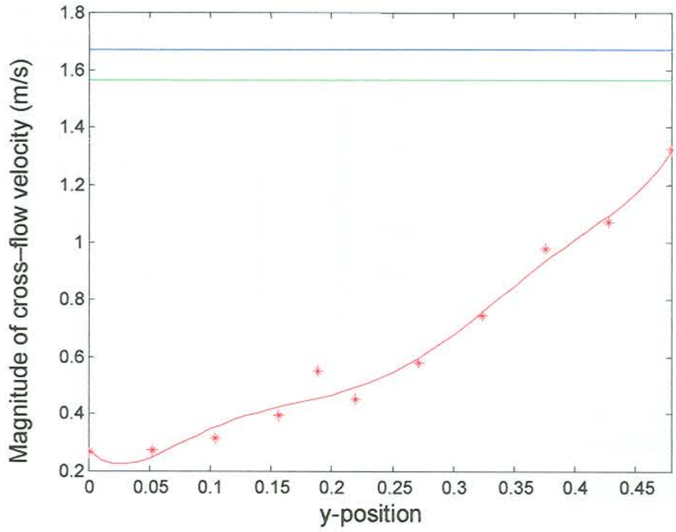
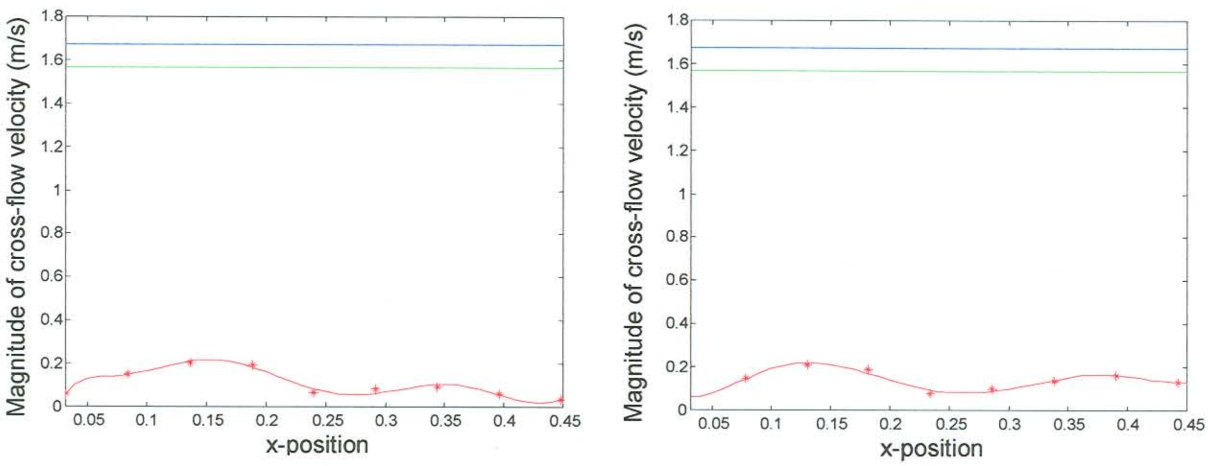


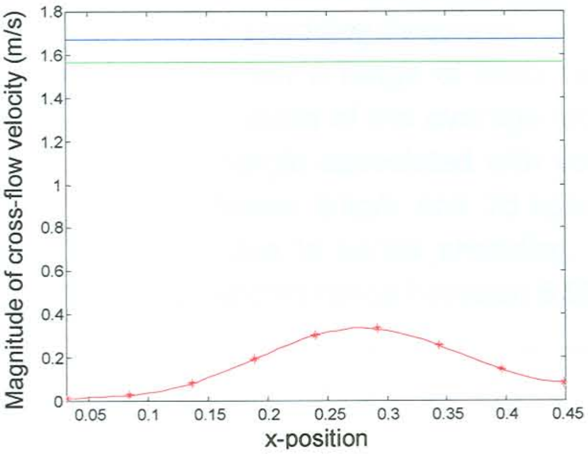
Figure 5.3: Magnitude of cross-flow velocity between baffle type 1 and 2 (at inlet section) for a mass flow rate of 8 kg/s.
(red – CFD results, blue – HTRI average cross-flow velocity, green – HTRI baffle tip velocity)

The unsupported tube length at the shell wall section does not experience the predicted HTRI average cross-flow velocity over the whole length, but only across the first section between baffle type 1 and 2. If a 20 percent margin of uncertainty on the HTRI average cross-flow velocity is used, only 1.3 percent of the tubes are subjected to a vortex shedding frequency that equals their natural frequency across a third of the tubes unsupported length. The vortex shedding frequency across the remaining tubes is well below the natural frequency of the tubes.

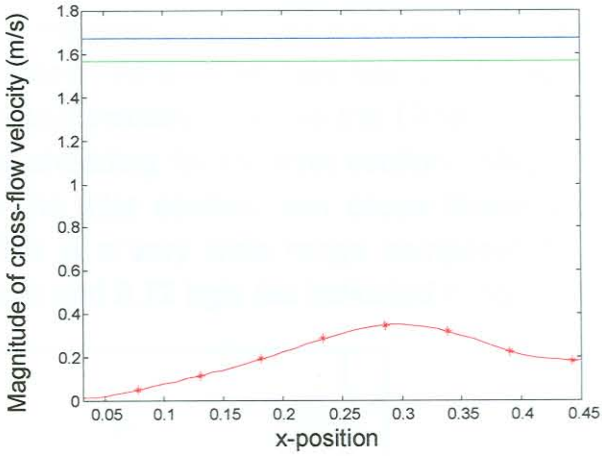


a) Bottom section *b) top section*

Figure 5.4: Magnitude of cross-flow velocity between baffle type 2 and 3 for a mass flow rate of 8 kg/s.
(red – CFD results, blue – HTRI average cross-flow velocity, green – HTRI baffle tip velocity)



a) Bottom section



b) top section

Figure 5.5: Magnitude of cross-flow velocity between baffle type 3 and 1 for a mass flow rate of 8 kg/s.
(red – CFD results, blue – HTRI average cross-flow velocity, green – HTRI baffle tip velocity)

The predicted HTRI mass flow rate at which vibration due to vortex shedding will occur for the inlet and middle sections is 7.95 kg/s and 8.004 kg/s respectively (table 2.1). These mass flow rates differ by less than 0.7 percent and only the 7.95 kg/s value will therefore be used in the following section. If the predicted HTRI average cross-flow velocity and baffle tip velocity associated with mass flow rate of 7.95 kg/s is compared to CFD average cross-flow velocities over a range of mass flow rates, different tubes at different positions in the heat exchanger, will be excited (figure 5.6).

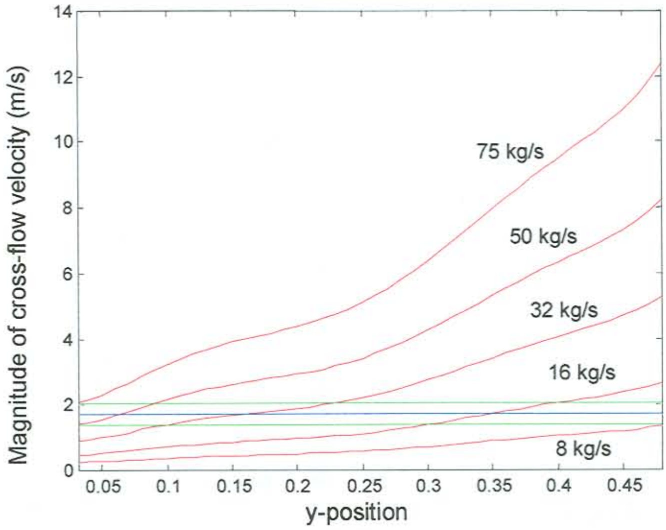


Figure 5.6: Magnitude of cross-flow velocity between baffle type 1 and 2 for a range of mass flow rates.
(red – CFD results, blue – HTRI average cross-flow velocity, green – 20 percent margin)

This implies that there is not a single mass flow rate that can be associated with the vortex shedding frequency, but that the heat exchanger is subjected to vortex shedding over a range of mass flow rates. At a mass flow rate of 75 kg/s, the CFD magnitude of the average cross-flow velocity is above the HTRI cross-flow velocity margin associated with vortex shedding for the inlet section. Mass flow rates between 8 kg/s and 75 kg/s in the inlet section, can cause flow-induced vibration due to vortex shedding. This is a very wide range compared to the HTRI predicted range between 6.95 kg/s and 9.72 kg/s (as indicated in figure 5.7)

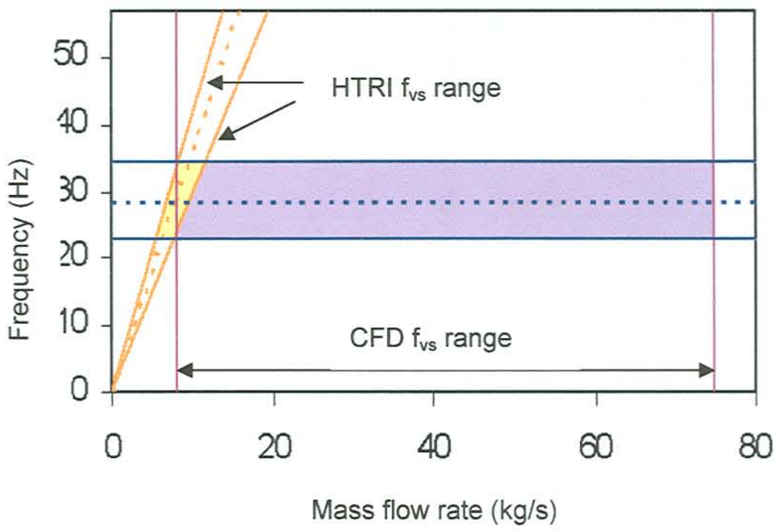
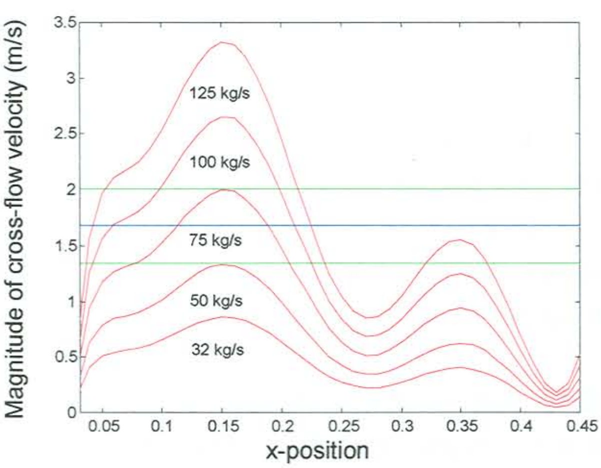
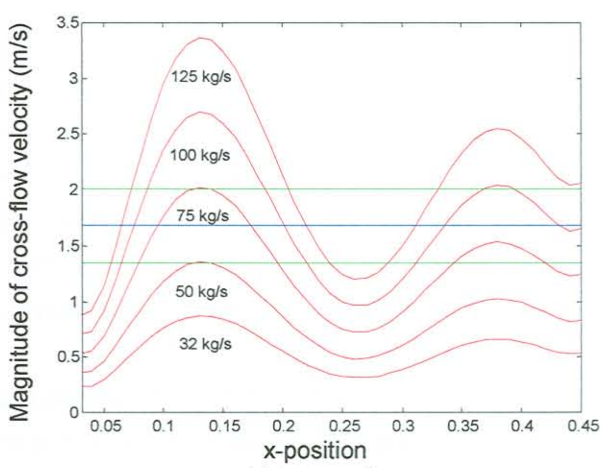


Figure 5.7: HTRI and CFD vortex shedding range

In the middle section of the heat exchanger, flow-induced vibration due to vortex shedding can occur from a mass flow rate of 32 kg/s and upwards. (Figures 5.8 a) and b), and 5.9 a) and b)).



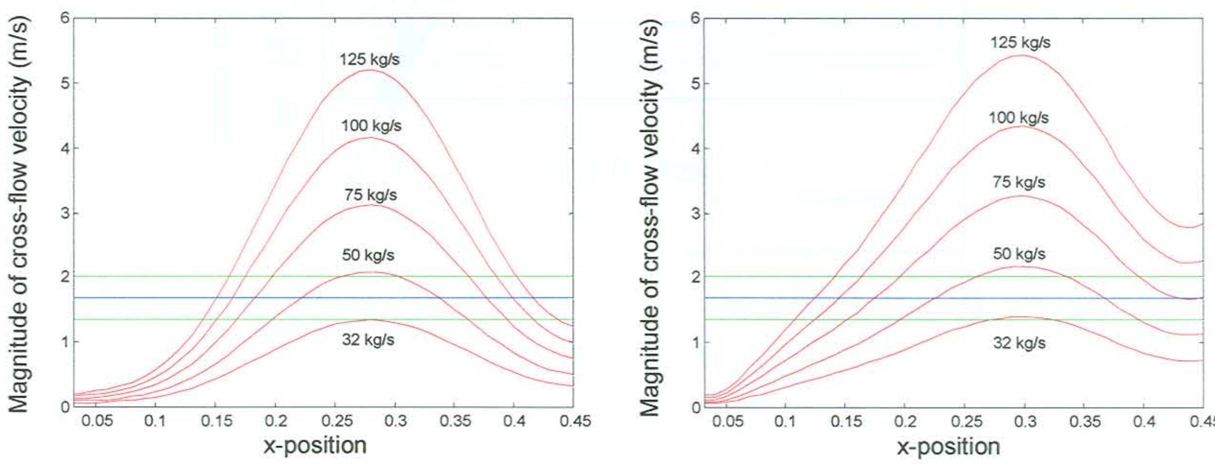
a) Bottom section



b) top section

Figure 5.8: Magnitude of cross-flow velocity between baffle type 2 and 3 for a range of mass flow rates.
(red – CFD results, blue – HTRI average cross-flow velocity, green – 20 percent margin)

The CFD analyses indicated that the triple segmental baffle directs the flow more parallel to the tubes and the cross-flow velocity is therefore not so high as in a double segmental baffle configuration.



a) Bottom section *b) top section*

Figure 5.9: Magnitude of cross-flow velocity between baffle type 3 and 1 for a range of mass flow rates.
(red – CFD results, blue – HTRI average cross-flow velocity, green – 20 percent margin)

5.3.2 Turbulence buffeting

The HTRI predicted mass flow rate at which fluid-induced vibration due to turbulence buffeting will occur is 9.982 kg/s and 10.054 kg/s for the inlet and middle sections respectively. The associated HTRI average cross-flow velocity for the inlet section mass flow rate of 9.982 kg/s is 1.93 m/s. The CFD magnitudes of the average cross-flow velocities were compared to the HTRI value of 1.93 m/s. A margin of 20 percent was used for the HTRI average cross flow velocity value. At the inlet section, the CFD analyses predicted a mass flow range between 9.3 kg/s and 77 kg/s where vibration may occur. The HTRI analyses predicted a flow range between 8.7 kg/s and 11.3 kg/s (using a 20 percent margin of uncertainty) as indicated in figure 5.10.

At the middle section the CFD analyses predicted that vibration, due to turbulence buffeting, would occur from a mass flow rate of 37 kg/s and upwards.

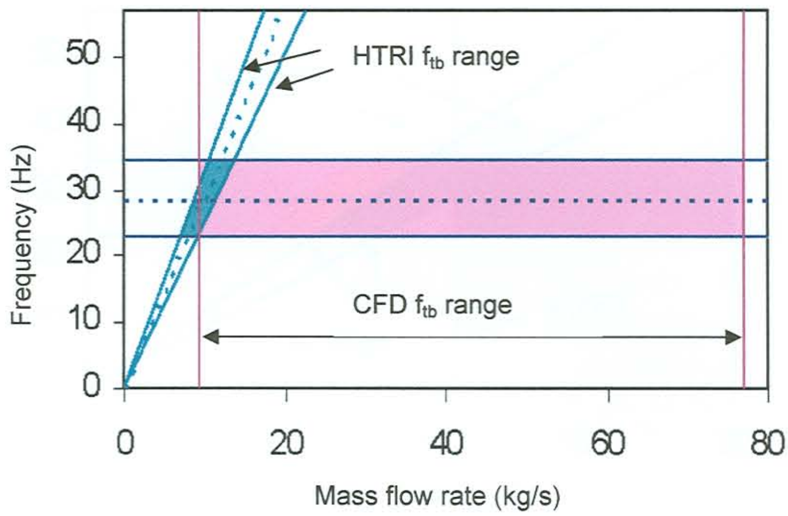


Figure 5.10: HTRI and CFD turbulence buffeting range

5.3.3 Fluid-elastic instability

The HTRI predicted critical velocity of 2.89 m/s (equation 2.2) was also compared to the CFD average cross-flow velocity values. The mass flow rate associated with the velocity of 2.89 m/s as 14.22 kg/s, as predicted by HTRI. If a 20 percent margin of uncertainty is used, the HTRI analyses predicts vibration due to fluid-elastic instability from a mass flow rate of 11.4 kg/s and upwards. The CFD analyses predicted a mass flow range from 14 kg/s and upwards.

If the CFD predicted mass flow ranges calculated for fluid-elastic instability, turbulence buffeting and vortex shedding are combined, flow induced vibration will occur from a mass flow rate of 8 kg/s and upwards. The HTRI analyses predicted what vibration will occur in the heat exchanger from a mass flow rate of 6.95 kg/s and upwards (as indicated in figure 5.11). The HTRI and CFD values compared well, only because in this specific case, the vortex shedding range overlapped with the turbulence buffeting range, which in turn overlapped with the fluid-elastic instability range.

If the vortex shedding, turbulence buffeting and fluid elastic-instability regions do not overlap (as shown in figure 5.12), safe operating zones are predicted by the HTRI analyses. The CFD analyses however do not predict safe operating zones after a certain minimum mass flow rate.

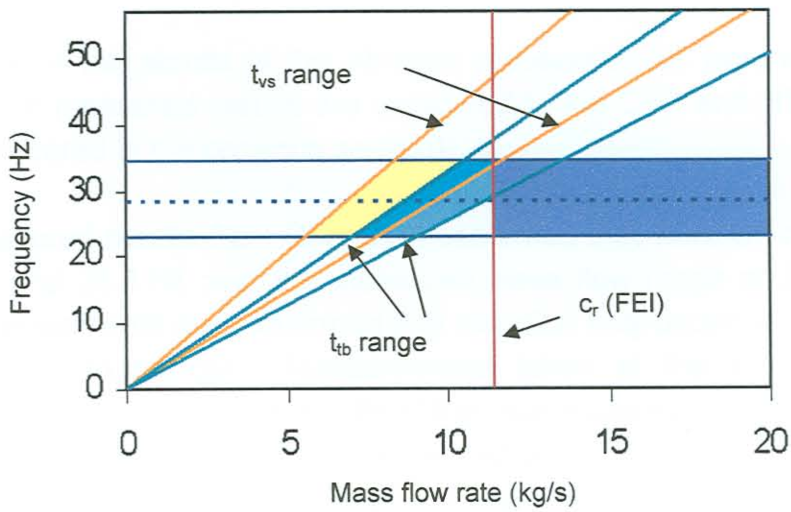


Figure 5.11: HTRI turbulence buffeting, vortex shedding and fluid-elastic instability range

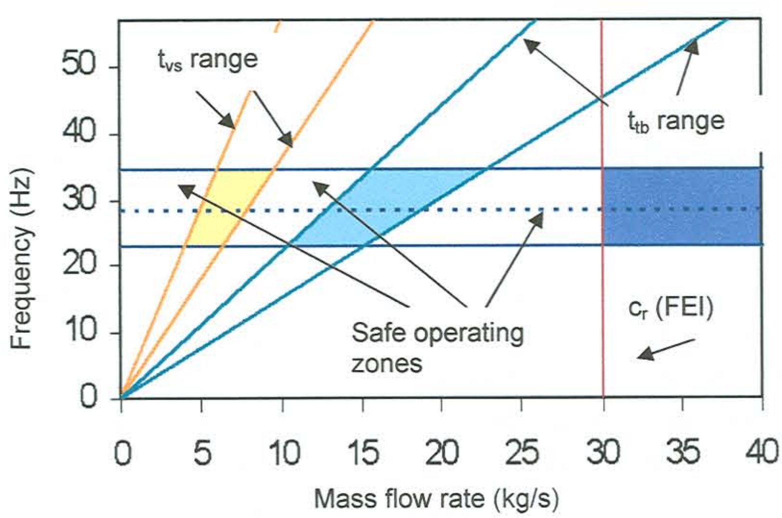


Figure 5.12: Turbulence buffeting, vortex shedding and fluid- elastic instability range

It is important to remember that only small sections of the tubes experience excitation at different mass flow rates. Even if the flow rate is within the above-mentioned range, vibration can only occur if the excitation forces on the sections of the tube are sufficiently large to cause the whole tube to vibrate.

The problem however, is that the unsupported tube length is not subjected to a constant average cross-flow velocity across the whole tube length, but the magnitude and direction of the cross-flow velocities differ over the tube length. The effect that this has on the tube's vibration, can only be obtained if a complete fluid-structure interaction analysis is done on the unsupported length.

5.3.4 Comparison of experimental results

In Chapter 4 the results of the vibration measurements were described. In this section the measured results are compared to the CFD and HTRI results (which were compared in the previous section).

The measured results from Chapter 4 confirmed that vibration did occur between 27.5 Hz and 28.5 Hz over the measured mass flow range of 3 kg/s to 100 kg/s. The measurements also confirmed that vibration only occurred in certain sections of the heat exchanger. Measurements taken at the supports of the heat exchanger, as well as at the middle of the heat exchanger shell (position B1 to B4 and R1 to R4), indicated vibration between 27.5 Hz and 28.5 Hz. The measurements at the inlet and outlet section of the heat exchanger did not detect vibration at the above mentioned frequency range.

The measured and HTRI predicted natural frequency, differs by less than 4 percent. The slight difference in the measured frequency, is because of differences in the way the tubes are supported at the baffle plates. The baffle hole clearances may differ due to manufacturing or corrosion of the tubes, or baffles. Corrosion can also cause the tubes' natural frequency to change due to a change in mass of the tube.

The measured flow range where vibration occurred, also compares well with the CFD predicted range (figure 5.13 and Appendix E). The amplitude of the vibration measurements on the shell and supports are very small. It was not possible to measure the actual tube vibration amplitude, but the HTRI analyses also predicted very small tube vibration amplitudes (0.3 mm) due to turbulence buffeting and vortex shedding. These analyses did not take the vibration amplitude due to fluid-elastic instability into account (figure 2.4). From the measured results, no increase in amplitude could be noticed if the mass flow rate was increased above the critical velocity.

Only vibration at the lowest natural frequency of the tubes was measured. No vibration at the other three natural frequencies, as described in Chapter 2, was detected. This may be because the amplitude of the vibration at the higher natural frequencies was too small and the strain gauge measurements only gave good results at lower frequencies.

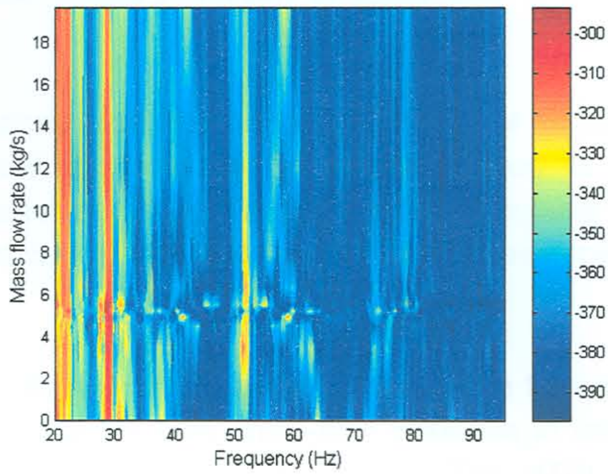


Figure 5.13: Contour plot of strain gauge measurements on the heat exchanger shell.

5.4 Margin of uncertainty

In Section 5.2 the HTRI average cross-flow velocities were compared to the CFD average cross-flow velocity values. Although the maximum CFD predicted velocity value differed by 20 percent, the remaining CFD predicted average cross-flow velocities varies between 20 percent to 99 percent from the HTRI predicted values at the predicted HTRI excitation mass flow rates. The following factors that influence the margin of uncertainty in the prediction of flow induced vibration were described in the previous chapters:

- The temperature and pressure variation at the shell-side inlet of the heat exchanger: In Chapter 2 a difference of less that 0.4 percent in vortex shedding and turbulence buffeting over the specified temperature range were calculated. The pressure variation at the inlet of the heat exchanger only affected the acoustic frequencies (174.75 Hz), which in this specific instance, could not lead to vibration because it did not coincide with the natural frequency of the tubes.

- The tube support assumptions that are used: FEM analyses in Chapter 2 calculated the difference in natural frequencies for different support configurations. If the wrong support configuration is used, a difference of 36 percent for this specific case was obtained.

- The clearance between the baffle hole and tube as well as tube and baffle corrosion: Corrosion in the heat exchanger influences the natural frequencies of the tubes, because of the reduction of mass and difference in the support configuration.

- The correlation values used in calculating the natural frequencies of the tubes: In Chapters 1 and 2, correlation graphs are used to obtain the natural frequencies of the tubes. The TEMA and HTRI calculated natural frequencies differ by 3 percent due to the difference in added mass coefficient (*k*) that was used.

- The flow patterns through the heat exchanger: The flow patterns through the heat exchanger can cause high cross-flow velocities in certain regions of the heat exchanger as described in Chapter 3. The HTRI analyses predicted velocities that are up to 99 percent higher than the CFD predicted average cross-flow velocities.

To quantify the margin of uncertainty in the prediction of flow-induced vibration, a more detailed analysis of the factors that influence the natural frequency of the tube are needed. These include better correlation values for different tube configurations and heat exchanger configurations, as well as a better representation of flow velocities through the heat exchanger.