

Chapter 6 – Conclusion and recommendation

This chapter outlines the main principles, findings and conclusions that were drawn from this study and proposes regions for future study and recommendations regarding the mitigation and solution possibilities of the issue under discussion.

6.1. Conclusions

CFD was effectively used to model and compare the performance of six STHE configurations. Studies from various authors were examined to investigate the suitability of modelling as well as the extent of investigations into STHEs. The work from these authors showed many experimental investigations into the flow patterns that occur in STHEs, but limited work on numerical studies of the flow characteristics were obtained, emphasizing the need for the present study.

The results that were obtained from the steady-state simulations showed conclusively the single-segmental baffled STHE with rotated square tube arrangement to have the highest velocities, crucial for sediment transport, but detrimental in terms of pressure drop. The other examined configurations are not feasible for use in flows with high sediment concentrations because of the high velocities that are required for sediment transportation.

From the flow patterns that were observed in the alternate configurations, the reason behind the higher heat transfer to pressure drop ratios was evident. The flow has a longitudinal nature, as opposed to the cross-flow observed in the single-segmental configurations. Because of the lower velocities, the pressure drop is reduced, in turn enabling higher mass-flow and increased performance.

The sedimentation that was observed in the single-segmental configurations was partially expected. Deposits were observed lower in the recirculation regions (corners) and can be assumed to accumulate on top of the tubes in the upper recirculation regions.

Although the Single_60 configuration displayed higher velocities, larger quantities of sediment further down the stream and less concentration build up, the results are not conclusive enough. The time it takes to simulate the simplified heat exchangers was still too long to prove the prominence of the configuration fully. For the particular computational arrangement, one time step of 150 iterations took 40 minutes to complete, simulating 0.001 seconds of flow and sedimentation. In total, roughly two seconds were simulated, which makes future predictions in the range typical of nine-month operational periods improbable and impractical with the computational resources currently available.

Another point of consideration is that the deposition rate is expected not be a linear function of time, further complicating predictions. The sedimentation rate would probably be largest in the early stages, decreasing in the intermediate stages and increasing up to a point of saturation. As the deposition increases, the areas of high concentration will inhibit the flow of cooling water. This effectively reduces the cross-sectional area, increasing velocity and the subsequent rate of transportation. At this point in the heat exchanger's lifetime the deposition and transportation rate would be in equilibrium. This occurrence is attributed to the increasing Reynolds numbers, in other words velocities, improving transportation.

6.2. Recommendations

There are certain significant aspects of the study that either fell outside the scope or were encountered during the literature survey that were essential for the full exploration and comprehension of the topic under consideration. Subsequently, these aspects are discussed and recommended for future investigation.

6.2.1. Configurations

Not all possible and available configurations were investigated. Future research could investigate similar flow characteristics for heat exchangers with the rotated square and triangular tube arrangements. Consideration should also be given to the discussion in Chapter 2.4 on tube surface modifications, incorporating the work of Hosseini *et al.* (2007:1008), Achenbach (1991:207), and Sparrow and Kang (1985:350). Different tube geometries were investigated by Hasan and Siren (2011:644) as well as Ibrahim and Goma (2009:2158), and could, along with other geometric alterations, have significant influence on the flow, pressure drop and heat transfer characteristics of the tube bundles.

Although simpler baffle geometries were tested, one can also investigate the applicability of triple-segmental baffles, helical baffles (continuous and middle overlapped), horizontal baffles or geometries of user design, as well as the configurations that were discussed by Yongqing *et al.* (2011:53) and Krishnan and Kumar (1994:624).

Two geometries proposed by the present author can also be considered. It is evident that the recirculation regions behind the baffles are the most problematic with regard to sedimentation. A viable option could be to divert part of the stream that flows over the baffle into the recirculation area by means of a secondary baffle. The goal of the baffle is only to increase the flow velocity in the recirculation zone, thus increasing velocity and transportation (Figure 80).

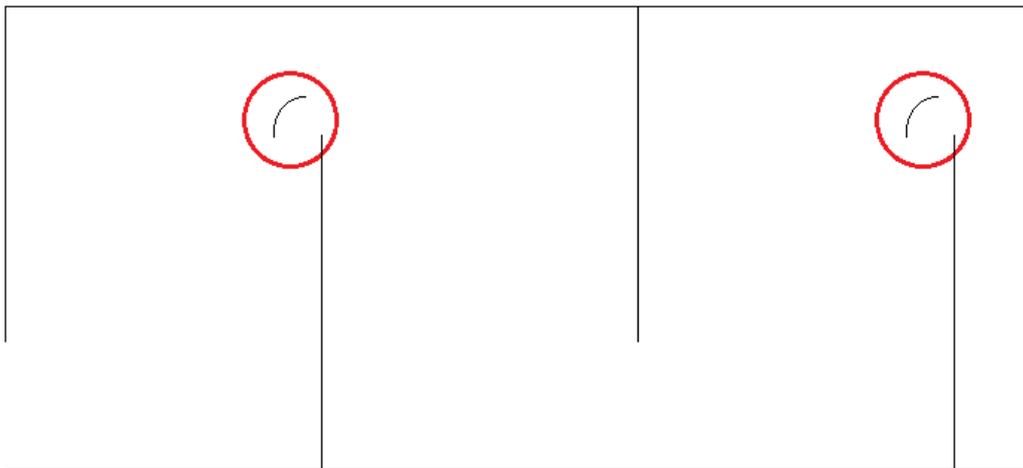


Figure 80: Position of secondary baffle for flow diversion

Secondly, if the use of cross-flow in shell-and-tube heat exchangers is continually shown to be problematic, it could be beneficial to consider moving away from this entirely. Although it has been shown that longitudinal flow over tubes is not nearly as efficient in heat transfer as cross-flow, it could alleviate the sedimentation problems. The design proposal is to implement several horizontal, longitudinal baffles situated between the tube rows (Figure

81). These heat exchangers will generally be larger or have fewer tubes due to the addition of extra baffle plates. Maximum flow velocity and tube support are two important issues to address in this design.

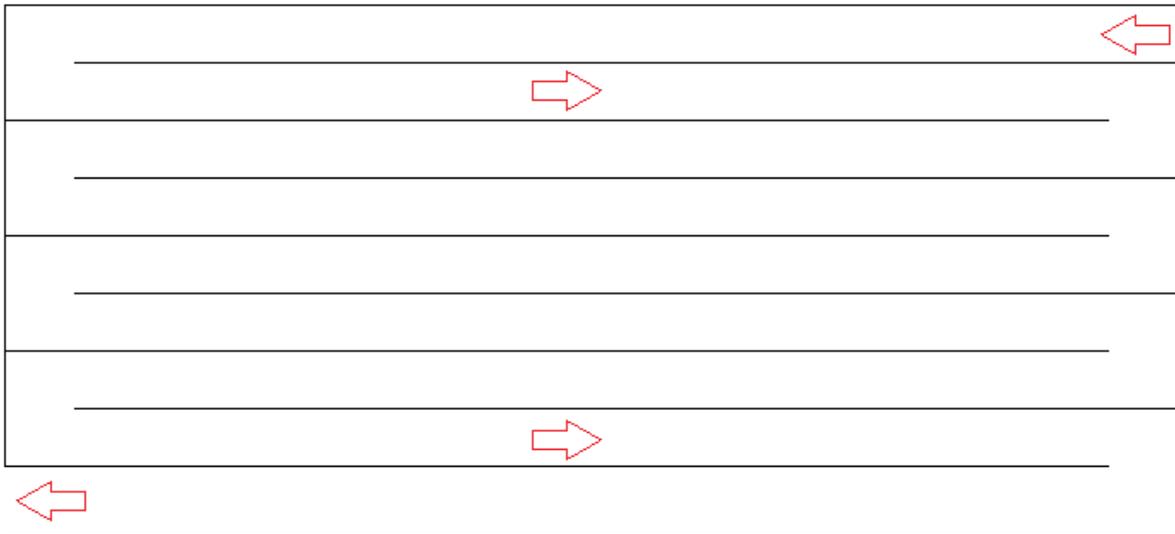


Figure 81: Longitudinally baffled heat exchanger

6.2.2. Heat transfer

As discussed in Chapter 1.3, heat transfer has been omitted from the simulations to simplify the solution and convergence of the intricate simulations. Heat transfer greatly increases the required computational capacity through the addition of the energy equation; the effect thereof on the flow velocities and particulate sedimentation could be substantial. Settling velocities will be affected due to the altered phase interaction characteristics that are caused by the high temperature dependence of viscosity (Lemmer, 2004; Lemmer, 2012). The effect on density is, however, less pronounced and the variability can be considered negligible at the heat exchanger's operating conditions.

6.2.3. Operating parameters

It was shown in Chapter 5 that the pressure drop of the configurations differ. The operating philosophy is generally such that heat exchangers are driven to operate at the maximum pressure drop allowed by the system, to achieve optimum heat transfer. From Chapter 2 it was determined that the other configurations studied have better heat transfer to pressure drop ratios. It might, thus, be beneficial to study the same parameters of the configurations at similar pressure drops, rather than constant inlet velocity.

6.2.4. Geometry and design

The influence on the simulated sedimentation patterns might be affected by other geometric factors that are not included in the present study.

The full length of the heat exchanger was not simulated simultaneously in both the steady-state and transient multiphase simulations. The small percentage of particles that might have crossed the outlet plane in the transient simulations could have had a possibility of being captured in the three remaining compartments.

The influence of not simulating the full heat exchanger length at once is evident in the steady-state simulations. A significant implication of this methodology is the absence of rearward communication between inlet and outlet boundary cells. Cells within the central mesh will have a constant forward and rearward information dependency, while the outlet and inlet boundary cells only have a forward flow of information. Once again, the influence of this on the thermo-hydraulic characteristics could possibly be significant and can only be quantified through a comparison of segmental and full numerical simulation of heat exchangers of similar design, or experimental results of the heat exchangers under consideration.

Due to the undesirably large mesh requirements that were observed, the baffle-shell and baffle-tube leakage were omitted to simplify the solution and enhance the convergence behaviour of the models. These two streams could, on average, account for between 15% and 44% of the total flow (Li and Kottke, 1998b:433; Mohammadi, 2011), dependent on the geometry and mass flow, and will influence the sedimentation behaviour in the areas of recirculation and low flow prone to deposition.

In the transient multiphase simulations, several other simplifying assumptions were made. The tube diameter, pitch and quantity were altered, which could modify the observed flow and sedimentation patterns to a lesser extent. The addition of sealing strips would greatly affect the observed flow patterns positively, but would also alter the observed sedimentation behaviour significantly. The modelling of nozzles fell outside the scope, but would show the first signs of sedimentation if it was included and could influence the flow slightly.

The alternate heat exchanger geometries that were modelled in this study were modified from the existing design. The modifications deviate from the original design intent (capacity, pressure drop and performance) and are thus not optimum. Taking the information from Chapter 2.2 into consideration, optimisation of altered geometries is an important aspect which could influence the observed flow characteristics significantly.

Future versions of the CFD software that had been used might have other modelling techniques (such as a multiphase realizable $k-\epsilon$ turbulence model) and improved solution algorithms which could have a positive effect on the stability and convergence behaviour of the simulations. Other options such as LES and DES, which are currently impractical due to computational restraints, might be feasible in the future.

If the increase of velocity by means of a larger pressure drop is impractical and unattainable, alternate options are possible. Pressure equipment design is not done with only process reasons in mind; maintenance plays an important part. If the system cannot allow the higher velocities that are brought on by increased pressure drops, the heat exchangers should be designed with maintainability in mind. This entails that a heat exchanger should not necessarily be designed for increased operating life, but possibly for removal of sediment at intermediate life-cycle periods. This could result in an extended heat exchanger operating life, in effect reducing cost over a larger time period.

6.2.5. Final recommendation

Solution or, at least, mitigation of the effects of sediment deposition could be attained by adjusting the baffle orientation by 90° (vertical baffle-cut), along with installing the heat exchanger at an incline. The adjustment would influence the sedimentation patterns, but,

more importantly, the restrictions that were brought on by the baffles would be eliminated, in other words there would be an unrestricted flow path, which is essential for transport of sediment across heat exchanger boundaries.

It might be feasible to consider the effect of increasing single-segmental baffle-cut in order to increase the pressure drop and subsequent velocities in the square tube arrangement. The assumption is made that transportation of sediment would be easier in a square arrangement in comparison to the rotated triangular arrangement, due to less restriction. On the other hand, the increase would generate further difficulties in enlarged recirculation areas behind baffles, which might have an increased detrimental effect.

The largest regions of concern are the recirculation zones behind the baffle plates where the effects of sedimentation are most severe. The difficulties that are experienced with these areas could be alleviated by other means. Vortex generators could be installed in such a manner that the flow and turbulence structures in the recirculation areas would be increased; the possibility of sediment suspension and transportation would thereby be increased, as well.

It is strongly recommended that the use of flow diversion into the recirculation areas of the heat exchanger, or longitudinally oriented flow be studied and considered as alternatives to the current design.