

7. CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

Under clean conditions, commercial Alfa Laval M3 diagonal and side flow plates exhibit similar heat transfer characteristics. This contradicts the theory that diagonal flow plates should have higher heat transfer than their side flow counterparts. In addition, both the pressure drop and the corresponding friction factor are slightly lower for diagonal flow plates than side flow ones. These trends could be due to the different flow patterns in their respective plate channels. In conjunction with a corrugated polycarbonate plate, visual observation of flow patterns in these channels were performed with a suspension of Acronitrile Butadiene Styrene (ABS) particles in water at room temperature. For both the diagonal and side flow set-ups, the flow velocity was observed to be fastest in the main flow region between their inlet and outlet ports, and slowest in the plate corners adjacent to these ports. With different flow paths, M3 diagonal and side flow channels have different local flow distributions, which contribute to their unique heat transfer and pressure drop characteristics.

Investigation of calcium sulphate (CaSO_4) precipitation fouling was carried out with Alfa Laval P01 and M3 plates, and custom-made flat plates with good repeatability of data. Effects of solution velocity, temperature, concentration, and port position were investigated using P01 and M3 diagonal flow plates. The fouling rate was found to increase with decreasing solution flow velocity, and increasing solution temperature and initial solution concentration. The rate of deposition is therefore, likely to be reaction-controlled rather than diffusion-controlled. These trends are similar to those previously published by Bansal (1994), who additionally found solution concentration to be important only in the initial stages of fouling. However, in the present investigation, fouling was observed to be strongly influenced by solution concentration top-ups during the course of an experiment. Furthermore, the time and amount of top-up also affect the resulting fouling behaviour. The topping-up times are marked by a sharper increase in pressure drop, but no such corresponding increase in

fouling resistance was registered. This is because the pressure drop increase was most likely caused by deposit formation near the outlet region of the plate which does not contribute much to heat transfer. In addition, M3 diagonal flow plates display slightly lower fouling resistances, and pressure drop values than their side flow counterparts. A similar overall change in pressure drop is however, observed for both plate types.

To enhance the understanding of deposit growth, visual observation of fouling pattern development was performed using M3 diagonal and side flow plates in conjunction with a corrugated polycarbonate plate. For both plate types, deposition first occurs in the plate corner adjacent to the outlet port, and an asymmetric fouling pattern was eventually formed. Hence, it was confirmed that high temperature and low flow velocity are the two criteria necessary for deposition to occur. When only one of the two is present, deposition may still occur but its rate would be very much dependent on the local conditions, such as surface roughness, surface material and degree of supersaturation. Furthermore, fouling was observed to commence at the contact points between adjacent plates. X-ray diffraction (XRD) analysis confirmed that gypsum (calcium sulphate dihydrate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) was the sole crystallising deposit. Despite inconsistent trends between set-ups with and without the polycarbonate plate, the former set-up reveals fouling patterns in M3 plate heat exchangers, and hence provides new insights into the effects of flow distribution on fouling. Results from the polycarbonate plate experiments were confirmed with a series of fouling experiments performed with the normal set-up, which were terminated prematurely to examine the fouling pattern at different run-times.

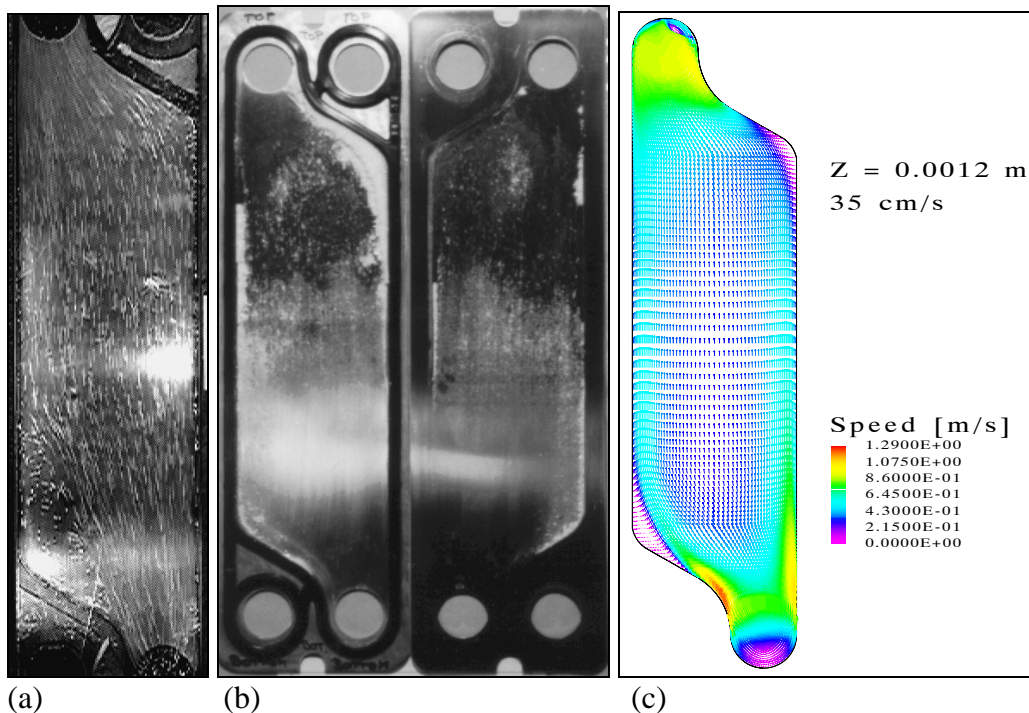
Several methods to mitigate fouling were investigated. Successful mitigation methods involved the addition of sodium nitrate (NaNO_3) into the process solution, solution velocity surges, and air flushes of the solution flow. Although the addition of NaNO_3 into CaSO_4 solution reduced fouling significantly, the amount of NaNO_3 used (30.0 g/l) was ten times more than the initial concentration of CaSO_4 (3.0 g/l). It can therefore be inferred that this method may neither be a cost effective nor an environmentally friendly way of mitigating fouling. As a method of removing pre-existing deposits on untreated stainless steel surfaces, velocity surge seems to be more effective in the presence of more abundant deposits. Air flush or the introduction of a

high air flow into the plate heat exchanger solution flow proved to be capable of removing a pre-existing fouling layer, and hence can be considered as an option for mitigating fouling. Conversely, continuous air injection into the solution flow, ion-sputtered plates and magnetic devices failed to reduce fouling. Continuous air injection promoted more deposition than that of single phase flow, such that even the fouling deposit patterns obtained were different. This may be a result of complex interactions between two phase flow and fouling. There seemed to be no apparent difference in the fouling behaviour between the untreated stainless steel plates and plates which are ion-sputtered with diamond-like-carbon (DLC), diamond-like-carbon and a silicon polymer (DLC & HMDSO), diamond-like-carbon and C_2F_2 (DLC & C_2F_2), and tetrahedral-amorphous carbon (ta-C). It is rather disappointing that not only ion-sputtering has not proved itself capable of mitigating fouling in plate heat exchangers, but also flushing of deposits attached to such plates has not been successful in terms of fouling reduction. Furthermore, it is inconclusive whether ta-C sputtered plates and a magnetic device could reduce the formation of $CaSO_4$ fouling in plate heat exchangers.

In order to simplify the analysis of the relationship between plate design and fouling, experiments were also carried out using 2-mm-thick, custom-made flat plates. As there are no contact points to maintain the plate channel gaps, non-uniform inter-channel gaps can occur in a flat plate heat exchanger. This has been substantiated by heat transfer and pressure drop analyses under clean conditions. Moreover, in the absence of contact points, thicker flat plates were required to counterbalance their lack of mechanical stability. This and the absence of corrugations which results in less mixing and lower turbulence level, cause a lower thermal efficiency to prevail for the flat plate heat exchanger when compared to that of a corrugated one. For a nominal solution flow velocity of 35 cm/s, corrugations bring about a heat transfer enhancement of about 5 times higher in the Alfa Laval M3 plates than that of the flat plates. Conversely, for the same solution flow velocity, the pressure drop for the Alfa Laval M3 plates is approximately 8 times higher than that of the flat plates.

Experimentation with flat plates revealed increased fouling with increase surface roughness and solution concentration. The latter trend is in accordance with that of the

Alfa Laval plates. Unlike the unsanded flat plates which exhibit a clear roughness delay time, the sanded plates which are smoother, have negative fouling resistances throughout the entire duration of the experiments. It therefore can be inferred that for the period the flat plates were allowed to foul, the increased turbulence brought about by the deposits penetrating into the laminar sublayer, outweighs their additional thermal resistance.



Figures 7.1(a), (b) and (c): (a) ABS particle flow pattern, (b) CaSO₄ fouling pattern, (c) CFD predicted flow distribution, for 35 cm/s solution velocity.

Experimentation using flat diagonal flow plates and a flat polycarbonate plate revealed similar flow and fouling patterns to those of the Alfa Laval plates. Figures 7.1(a), (b) and (c) serve to compare the flow pattern of the ABS particles obtained at room temperature for a solution flow velocity of 35 cm/s, with its corresponding CaSO₄ fouling pattern and flow distribution with heat transfer predicted using CFD. In these figures, the flow enters and leaves via the lower and upper ports respectively. Figure 7.1(a) shows a large zone of low flow velocity in the lower plate corner, and a smaller one in the upper corner. Since the upper part of the plate is hotter than the rest of the plate, deposition starts at the upper plate corner before proceeding to occur at

the lower plate corner. This further confirms that low flow velocity and high temperature are the two criteria necessary for fouling to occur. In addition, the fouling deposits formed a wavy front at the plate inlet region, where local areas with less fouling correspond to areas where the prevailing local flow velocity is higher, and vice versa. Furthermore, with a constant volumetric flow rate, fouling was observed to decrease with decreasing plate channel gap. This is because as the channel gap decreases, the corresponding flow velocity increases. Thus, it can be concluded that the prevailing flow velocity has a profound influence on the resulting fouling behaviour.

Five distributor designs, namely designs A to E were examined experimentally. Designs A to D have distributors in the flat plate inlet and outlet regions only. In order to prevent the occurrence of fouling, these distributors aim at directing flow to the low-flow-velocity zones in the plate corners adjacent to the ports. However, additional regions of low flow velocity are created in the wake of these distributors, and with nothing to break up these unfavourable regions, more deposition occurred on these plates when compared to (bare) flat plates without any distributors. Furthermore, larger plumes of deposits tend to form in the wake of longer distributors, thus making them inferior to shorter ones. As fouling develops, the fluid flow characteristics in a plate channel may alter completely, for instance, deposit growth can reduce the effective width of a plate, thus reducing the cross-sectional flow area. In addition, the presence of the distributors also raises the clean pressure drop of the channel. As inlet distributors distribute inflowing fluid across the plate channel, while outlet distributors only 'collect' flow into the outlet port, the former are more influential on the flow distribution, and hence the resulting fouling pattern. Therefore, in order to avoid the creation of large low-flow velocity zones and high pressure drops, extra care should be taken in designing these distributors. Emphasis should not only be given to the designs of the inlet distributors, but should also be given to ways of breaking up any additional low-flow-velocity zones generated. In addition, preference should be given to short distributors instead of longer ones.

Using an approximate fouling model, the fouling behaviour of plate heat exchangers which are 'overdesigned' with additional parallel plates, larger plates of different aspect ratios and additional plates in a second pass, was assessed. For adhesion-

controlled fouling, the flow velocity effect is more profound than that of the temperature. As the addition of parallel plates results in a reduced flow velocity in the plate channels for constant flow rates, this traditional method of excess heat transfer area incorporation is unsuitable if adhesion-controlled fouling is expected. In the presence of this fouling mechanism, the excess area is best incorporated by having a two pass arrangement, or by using plates with half the standard plate width. These methods result in higher flow velocities capable of increasing the removal rates of fouling deposits. With a higher flow velocity however, a higher pressure drop and higher pumping cost are also unavoidable.

On the other hand, the prevailing temperature has a dominant effect on the rate of reaction fouling. With the exception of the two pass arrangement and plates with half the standard plate width, the average wall temperatures of all the 'overdesigned' heat exchangers are comparable. Consequently, there is not much difference in their heat transfer performance in the presence of reaction fouling.

As flow characteristics play a major role in fouling in plate heat exchangers, flow simulations have been performed using a commercial CFD package, CFX. For flow through a 2-D channel with a single corrugation on the bottom surface, two areas of flow recirculation were observed. In addition, flow passing through 2-D channels with multiple corrugations on the top and bottom surfaces was also simulated. For plates with a 90° corrugation angle, both the simulated heat transfer and pressure drop increase with decreasing corrugation wavelength. On the other hand, increasing the plate channel gap causes the heat transfer and pressure drop to decrease.

The $k-\varepsilon$ model and the Differential Reynolds Stress Model (DSM) underpredict the point of reattachment for air and water flowing past a 2-D backward-facing step by 23% and 29% respectively. Although the overall and local flow patterns predicted by DSM bear a closer resemblance to that observed experimentally, the $k-\varepsilon$ model is able to capture the expected overall flow pattern successfully in less Central Processing Unit (CPU) time.

In addition to the actual flat plate channel with geometry similar to that of the Alfa Laval M3 plate heat exchanger, two simplified channels, namely a double backward-facing step, and a flat plate channel with flat inlet and outlet, were also simulated. Moreover, simulations were performed to obtain more reasonable input values of k and ε for these plate channels. The simulated values are larger than those calculated using equations given in AEA Technology (1995) by approximately 50 to 80%. For a steady, isothermal, incompressible, turbulent flow past a double backward-facing step, the simulated recirculation zones obtained using the k - ε model diminish in size as the dimension is changed from 2-D to 3-D. On the other hand, for the other simplified plate geometry, an interesting cold region in the plate corner adjacent to the outlet is observed for laminar flow with heat transfer. This cold region is however, not observed for turbulent flow in the actual flat plate channels.

Fluid flow in the true geometry of a flat plate heat exchanger was simulated under conditions similar to the fouling experiments performed. Steady laminar flow, steady turbulent flow using the k - ε model, and transient turbulent flow using DSM were examined. These models all underpredict the reattachment length, with laminar flow giving the most unrealistic results. Although DSM is able to predict a larger area of recirculation in the plate corner adjacent to the inlet port, the k - ε model gave a better estimation of the reattachment length and the pressure drop across the channel. Moreover, the required CPU time for DSM under transient conditions, is about two orders of magnitude higher than that for the other flow models. The flow distribution predicted using the k - ε model is shown in Figure 7.1(c). As can be seen, the k - ε model is capable of predicting the overall flow characteristics with reasonable accuracy and in relatively short CPU time. Thus, CFD can be inferred as a validated tool for predicting the overall flow characteristics in plate heat exchangers.

Eight distributor designs, of which five were examined experimentally, were simulated using the k - ε model. The simulated regions of low flow velocity and high temperature agree well with the locations of fouling deposits obtained in the corresponding experiments. The additional designs simulated further confirm that, in eliminating the original regions of low flow velocity present in the flat plate channels without distributors, blockages in the distributor and/or main heat transfer areas create

extra regions of low flow velocity favourable for fouling to occur. Moreover, these blockages also bring about a corresponding increase in pressure drop. It is however, difficult to compare the flow in the main heat transfer area of all these designs with the zigzag fluid motion in commercial chevron plates.

One way of achieving a more even distribution of flow in flat plates with the present Alfa Laval M3 geometry is to redesign the plate geometry such that the plate corners adjacent to the ports are smoother. Simulations show that this redesigned geometry has no recirculating flows in the plate corners, and hence should be less susceptible to fouling.

7.2 Recommendations for Future Work

Based on the encouraging findings mentioned above, several recommendations are put forward for future investigations:

- (i) Precipitation fouling of another salt, e.g. calcium carbonate (CaCO_3) or calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$), and multicomponent fouling would be most interesting to investigate. The difference between the deposit structure of single and multiple salt precipitation is worth examining. This is because single-salt solutions tend to form hard, tenacious deposits, while solutions containing salt mixtures tend to precipitate in an irregular pattern on the surface. The latter type of deposit is softer and less adherent, moreover its irregular surface promotes erosion by the fluid flowing over it (Garrett-Price *et al.*, 1985). Hence, it might be possible to reduce the overall fouling rate by promoting salt mixtures to precipitate. Even if the resultant softer deposit remains attached to the heat transfer surface, it would be easily removable.

- (ii) In order to visualise flow pattern and fouling pattern development better in commercial plate heat exchangers, e.g. Alfa Laval M3 plates, the corrugated polycarbonate plate used should have sinusoidal grooves instead of rectangular ones. Moreover, other plate materials with greater transparency are worth investigating. A highly transparent plate with sinusoidal imprints can be used to

visualise the zigzag motion of fluid flowing in different plate channel designs more clearly and accurately.

- (iii) The effect of added chemicals has only been studied for one concentration of NaNO_3 which reduced fouling dramatically. For this fouling mitigation method to be more cost effective and environmentally friendly, it is essential to investigate if lower concentrations of NaNO_3 would have the same effect on the precipitation fouling of CaSO_4 . The addition of different chemicals which have either a salt-in or salt-out effect, or a combination of different chemicals into the process solution would certainly give some interesting results.
- (iv) Anomalous results were obtained in the presence of two phase flow and fouling. Therefore, more experiments with different air flow rates, and visualisation of two phase flow will be required.
- (v) Although the ion-sputtered plates investigated have not reduced fouling, other different ion-sputtered plates, especially ta-C may be able to mitigate fouling successfully. In addition, due to the success of ion-implanted heater rods in mitigating fouling (Müller-Steinhagen and Zhao, 1997), experimentation with ion-implanted plates should be pursued. Successful application of ion-sputtering and/or ion-implantation on heat exchanger plates may bring about significant economic advantages.
- (vi) To enhance the understanding of the relationship between plate design and fouling further, visual observation of flow characteristics and fouling pattern development using custom-made plates with blockages which resemble corrugations in the commercial plates, in both the plate distributor and main heat transfer areas should be carried out.
- (vii) The present work on CFD needs to be extended to model 3-D flow channels with geometry similar to those of the commercial chevron plates. This is so that the zigzag motion of fluid observed experimentally can be simulated. Once the results for these flow simulations are validated, improvements in the present plate design

can be predicted with confidence via CFD simulations. In addition, instead of imposing a fixed wall temperature for the plate channel, heat transfer simulations with a three channel set-up similar to that used experimentally, should give results which better resemble those obtained experimentally. Although these CFD implementations would give more insights into the flow, heat transfer and pressure drop characteristics in a commercial plate heat exchanger, greater computational resources would be required.