HEAT AND MASS TRANSFER CHARACTERISTICS OF AN ANNULAR SIEVE TRAY

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An internally heat integrated distillation column, HIDiC, offers the maximum energy saving potential for difficult and energy intensive separations, such as propylene-propane and the like, which are carried out in tray columns. A novel type of HIDiC was developed by TUDelft, namely a concentric distillation column in which a low pressure annular stripping section is configured around a high pressure rectifying section. Due to a large heat transfer duty requirement per tray, heat transfer panels are placed on the active area of the distillation tray. Experimental results are presented for both the overall heat transfer coefficient between stripping and rectifying section and the separation efficiency of an annular stripping section sieve tray equipped with heat transfer panels.

KEYWORDS: heat integration, HIDiC, distillation, overall heat transfer coefficient, tray efficiency

INTRODUCTION

Distillation columns, which are often regarded as the working horses of the chemical and process industries, are known for their large energy consumption. In a distillation column heat is used as separating agent. In conventional distillation columns low pressure steam is usually used as heat source for the reboiler and cooling water is used as heat sink at ambient temperature. The temperature difference between heat source and heat sink causes the overall thermodynamic efficiency of a conventional distillation column to be lower than 10% (1). The separation process itself however, appears to be very efficient.

A very efficient but capital intensive way to improve the efficiency of a single distillation column is the use of direct vapour recompression. In a vapour recompression column (VRC) (Figure 1), vapour leaving the top of the distillation column is compressed to such a pressure and temperature level that it can be used as heat source for the bottom reboiler. However this appeared to be cost effective only for large capacity, close boiling separations like propylene/propane and similar.

The HIDiC concept also uses direct vapour recompression to enhance the energy efficiency of a single distillation column (Figure 1). In a HIDiC the rectifying section is operated at higher pressure than the stripping section by compressing the vapour leaving the stripping section and entering the bottom of the rectifying section. Consequently the rectifying section is operating at a higher temperature than the stripping section and heat can be transferred from rectifying to stripping section. Heat required to evaporate

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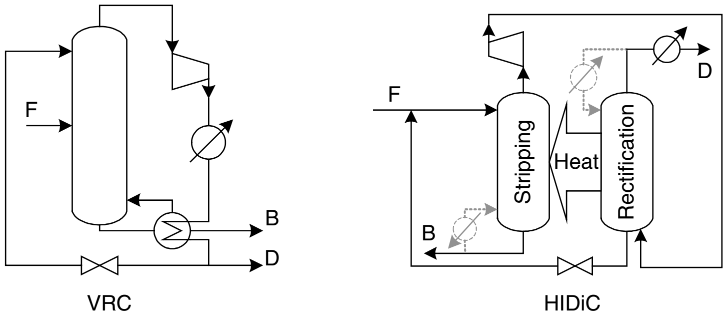

Figure 1. Schematic representation of the vapour recompression column and the HIDiC

liquid in the stripping section is delivered by the heat of condensation in the rectifying section. Because (part of) the liquid in the stripping section is evaporated internally, the external reboiler duty will decrease compared to the conventional distillation column, in ideal case to zero. In other words, in an ideal HIDiC no external reboiler is required. The basic advantage of HIDiC compared to VRC is that the heat pump operates over only a part of the distillation column, namely the stripping section. As a consequence the compression ratio can be halved with respect to that of a VRC for a given separation (2).

Although the HIDiC concept was already introduced in the seventies (3) and a lot of research was carried out until this moment (4–6), HIDiC is still not implemented in industrial practice. The main barrier for industrial implementation is obviously the complexity of the column design and also the lack of experimental data at sufficiently large scale to prove the practical feasibility of the HIDiC principle. From 1996 a Japanese consortium published experimental results of pilot plant experiments in a HIDiC which is constructed like a shell and tube heat exchanger, in which the tube side is the rectifying section and the shell side is the stripping section. Column internals can be both random or structured packings (7).

The concentric column concept introduced by Govind (5) has been further developed with respect to heat transfer devices to be placed between the trays of the rectification or stripping section (8). A HIDiC is especially favourable for the separation of close boiling mixtures, which however is associated with large heat transfer duties per stage, therefore a lot of internal heat transfer area has to be installed inside the distillation column (9). It is known from industrial practice that close boiling mixtures are separated in tray columns as structured or random packing cannot handle efficiently the large liquid loads in these applications. Therefore a tray appeared to be the preferred column internal for a HIDiC. In the proposed HIDiC design, which is basically a concentric distillation column, heat transfer area is provided by heat transfer panels which are placed preferably in the stripping section (Figure 2). In that case, vapour from the rectifying section should

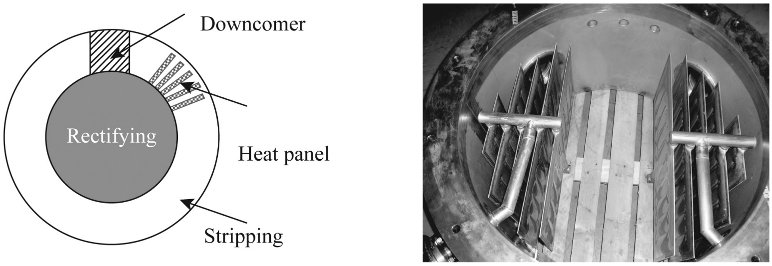

Figure 2. Placement of heat transfer panels in stripping section (a) and orientation of heat transfer panels in pilot plant (b)

enter the panels, condense inside and the condensate will flow back into the rectifying section. On the outer surface of the panels simultaneous evaporation of the liquid film will take place in the stripping section. It should be noted here that the driving force for vapour to enter the panels is the under-pressure created by the condensation of the vapour inside the panels, as there is virtually no pressure difference between the inlet and outlet of the panels. Although pressure drop calculations showed that the condensation process should start spontaneously, it is clear that this should be validated experimentally. Moreover very little is known of heat transfer characteristics in the froth of an operating distillation tray. Experimental values for both heat transfer coefficient and Murphree tray efficiency for a laboratory scale, 0.1 m diameter sieve tray, in which the heat was provided by means of an external heat transfer medium circulating through a coil mounted inside a thick sieve tray, were reported by Kaeser et al. (10) for the model system methanol-water.

The overall heat transfer coefficient is the key parameters in HIDiC design and should be determined experimentally.

EXPERIMENTAL

A pilot plant has been built at TUDelft, which is basically an annular sieve tray column in which heat transfer panels can be placed in either the downcomer or on the active area of an operating tray. The column data are summarized in Table 1. The model system for this study was cyclohexane/(n)-heptane. The column is operated at atmospheric pressure under total reflux and samples can be taken from the top and bottom products in order to determine the separation efficiency. The samples were analysed with Gas Chromatography. View glasses were mounted in order to visually observe the behaviour of the froth on the distillation tray. Figure 2 shows the layout of the heat transfer panels which were placed at the annular tray deck in this study. The height of the panels was 300 mm and the distance between the panels 30 mm. The panels were placed more or

Table 1. Distillation pilot plant data

Diameter outer column	800 mm
Diameter inner column	300 mm
Number of trays	3
Tray spacing	500 mm
Hole size	10 mm
Hole pitch	30 mm
Downcomer area	0.08 m^2

less in the direction of the liquid path at a distance of 90 mm above the tray in order to avoid interference with the liquid flow over the tray.

In order to measure the overall heat transfer coefficient a separate setup was built to feed the heat transfer panels with hydrocarbon vapour. This external column simulates behaviour of the rectifying section. Pressure is adjusted to create desired temperature difference between two sections accordingly. The vapour is slightly superheated to avoid condensation inside the setup, before the vapour has entered the heat transfer panels. Part of the vapour that flows upwardly enters into the heat transfer panels and condenses inside. The condensate quantity is measured using an in-line coreolis mass flow meter.

MODELING

The outside heat transfer coefficient of the evaporating falling liquid film is described using a sophisticated model proposed by Alhusseini et al. (11) for the transition regime between laminar and turbulent flow conditions. The inside heat transfer coefficient was modelled with the Nusselt equation as the condensate flow appears to be laminar and the Nusselt equation has proven its applicability for modelling the heat transfer behaviour of a laminar condensate film. (12)

The separation efficiency of the annular sieve tray was estimated using the model proposed by Garcia and Fair (13), which appeared to be the most appropriate model to determine the separation efficiency of a conventional cross flow sieve tray for the model system cyclohexane/(n)-heptane. The model is based on the two-film mass transfer theory. Because of the different regimes occurring in different sections on the tray, it is divided into six zones, of which five are relevant to mass and heat transfer. These five zones are modelled separately. In this model it is assumed that the gas phase moves in plug flow and that there is no vertical change in liquid composition across the tray. The gas phase residence time and the interfacial area for mass transfer are determined for each zone, depending on the type of two-phase system present (e.g. jetting, bubbling). In some zones there is a bubble size distribution. A bimodal size distribution is used, with large bubbles with a diameter of 25 mm and small bubbles with a diameter of 5 mm. Separate mass transfer contributions are calculated for the small and large bubbles within one zone. The contributions of the different zones and bubble sizes are then brought together to calculate the liquid phase efficiency.

RESULTS AND DISCUSSION

HEAT TRANSFER

Figure 3 shows the overall heat transfer coefficient for the panels placed on the active area of the tray as a function of the temperature difference between rectification and stripping section.

The overall heat transfer coefficient is high for low driving forces because at these conditions only a very thin laminar condensate film is formed on the inside wall of the heat transfer panels. Incomplete wetting occurs at very low film Reynolds numbers, which leads to a higher condensation side heat transfer coefficient as more surface area is available for the vapour to condense. An increase in the overall temperature difference leads to higher duties and consequently higher condensate flows. The condensate film thickness increases and as the film still remains laminar, the resistance for heat transfer increases. Consequently the overall heat transfer coefficient will drop to more or less constant value at increasing temperature differences, so the condensation side heat transfer coefficient appears to be the controlling parameter in this heat transfer process. Visual observation showed that the panels were sufficiently wetted by the splashing liquid present on the tray deck and no dry spots on the outer surface of the panels were observed.

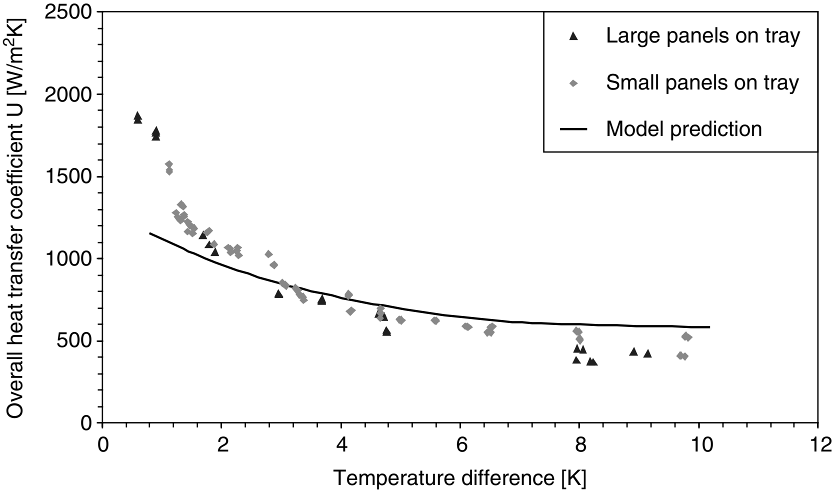

Figure 3. Overall heat transfer coefficient for heat transfer panels placed on active area of annular tray

The model prediction appears to be good except for the very low temperature differences, due to the fact that a stable liquid film cannot be formed at these low temperature differences because of the very low condensate flows. Moreover the experimental error is largest in this region, a slight heat loss to the environment could lead to condensation to the column wall and therefore lead to an over estimation of the experimental value of the heat transfer coefficient. Since a trayed HIDiC is not intended to operate at these very low temperature differences between rectifying and stripping section, it can be concluded that the model is suitable for the temperature region which is of practical interest for a HIDiC.

SEPARATION EFFICIENCY

Figure 4 shows the overall tray efficiency of the annular sieve tray as a function of the column load expressed as the F-factor, including the efficiency of a conventional cross-flow sieve tray which was tested with the mixture cyclohexane/(n)-heptane by Yanagi et al. at the Fractionating Research Inc. (14). In both cases, at low column loads the tray efficiency drops sharply due to weeping. The sieve tray tested by FRI starts to weep at a slightly higher F-factor due to the fact that the hole area of their tray was 14% compared to 10% for the annular tray which was used in our study. The upper operating limit is determined by flooding i.e.: entrainment of liquid to the upper tray. Unfortunately it was not

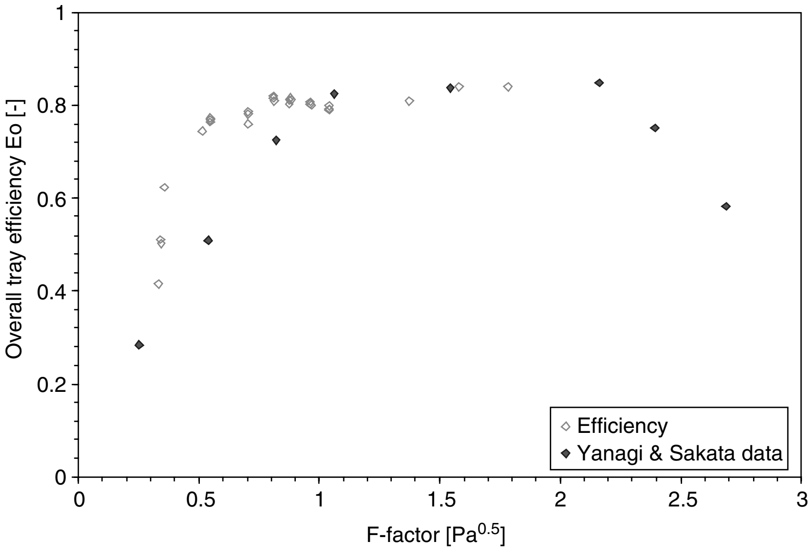

Figure 4. Overall tray efficiency of annular tray compared to conventional cross flow sieve tray tested by FRI

possible to determine the flooding point in our test rig due to limited reboiler capacity. The main and most important result, however is that the overall column efficiency in the regime in which the sieve trays are operated in practice, is equal for both tray layouts. Apparently the annular shape of the tray doesn't influence the Murphree tray efficiency. One could expect a difference in tray efficiency, because the liquid path length at our tray is not constant but changes from roughly 200 mm along the inner tube to 950 mm along the outside as a consequence of the annular shape of the tray. At a conventional sieve tray however, the distance between the inlet downcomer and outlet downcomer is constant. Apparently the liquid is so thoroughly mixed at both the tray deck and in the downcomers that the difference in liquid path length doesn't influence the overall mass transfer efficiency.

Figure 5 shows that the efficiency of the tray with heat panels is higher than that of an empty tray. Also it was found that there is hardly any difference between the cold panels and the panels which were in operation. This is most probably due to the fact that the amount of vapour formed at the outer surface of the heat panels was small compared to the total vapour flow in the column. It should be noted that in our test rig the liquid samples were taken from the top and the bottom of the column and only one tray out of three was equipped with heat transfer panels. So two trays were operating without panels and the effect on the average tray efficiency was determined and plotted in Figure 5. The enhancing effect on the single tray efficiency is even more pronounced

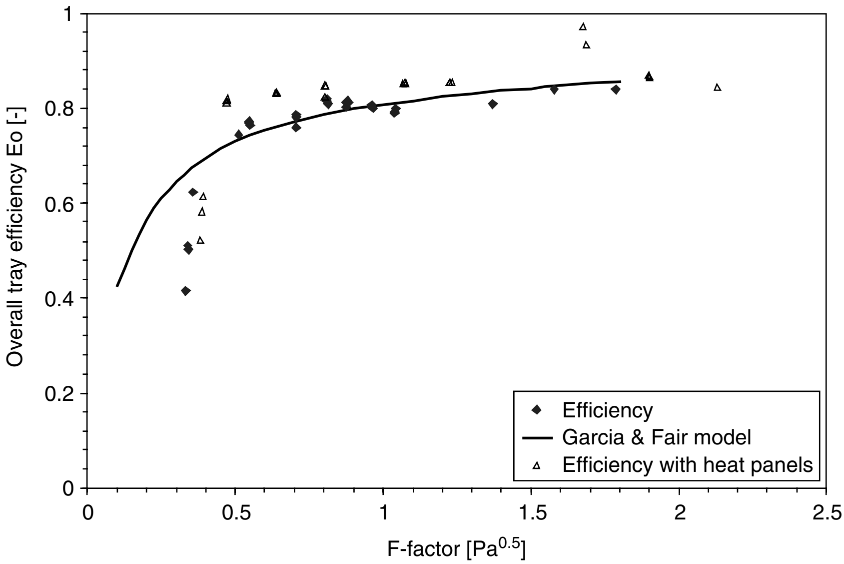

Figure 5. Overall tray efficiency as function of F-factor

and back calculation shows that the increase in efficiency for the single tray operating with heat panels is around 10%. Obviously the panels do have a positive influence on tray efficiency. Most likely the panels, which are placed well above the clear liquid (weir) height, hinder the backmixing of the froth on the tray deck, which results in an increased driving force for mass transfer. Analogous behaviour was reported in literature where baffles were placed on the active tray area to enhance tray efficiency (15). As observed during the experiments, the presence of heat panels didn't influence the tray pressure drop significantly.

CONCLUSIONS

Semi-industrial scale experiments have been performed with a concentric HIDiC column to establish the overall heat transfer coefficient and efficiency of an annular sieve tray equipped with heat transfer panels. Process fluid for both the condensing side and evaporating side of the heat transfer panel was a mixture of cyclohexane and n-heptane. The heat transfer coefficient is strongly dependent on temperature driving force due to laminar flow conditions at the condensation side. Overall heat transfer coefficients were between 800 and 1500 W/m^2K for temperature differences between 5 and 2 K.

Comparison of the data obtained in this study with measurements by the Fractionating Research Inc. shows that separation efficiency of an annular sieve tray resembles that of a conventional cross-flow sieve tray.

Heat transfer panels do have a positive influence on the separation efficiency of the tray, with roughly a 10% increase, without a penalty on the pressure drop side, which proves to be a strong advantage of the proposed column design with heat transfer panels placed above the active tray area.

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