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Characteristics of thermosiphon reboilers

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Abstract—The paper describes the operational characteristics of thermosiphon reboilers on the basis of an experimental and theoretical study. The operational responses to a variation of the driving temperature difference, the operating pressure and the liquid head in the inlet line are discussed in detail. Furthermore, the influence of several design parameters as length and diameter of the pipes is presented. The effects of all these parameters are explained by a simplified model that subdivides the evaporator into a heating and an evaporation zone. The variations of the length of these two zones are decisive for the operational characteristics of thermosiphon reboilers. © 2001 Éditions scientifiques et médicales Elsevier SAS

thermosiphon reboilers / reboilers / heat transfer

Nomenclature

d_i	inner pipe diameter	mm
h	liquid head	m
L	pipe length	m
p	pressure	bar
$\dot{q}$	specific overall heat flux	$\mathrm{kW \cdot m^{-2}}$
ΔT	driving temperature	K
$w \cdot \rho$	mass flow density	$\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$

1. INTRODUCTION

Of all reboiler types, vertical thermosiphon reboilers are most widely used in chemical industry. They are characterized by high heat transfer rate and low fouling tendencies. When designed and operated properly, the liquids have short residence times in this reboiler type what minimizes the risk of thermal degradation. This reboiler type is very reliable, has far lower operating costs than other reboilers, is easy to set up and has compact dimensions [1]. Thermosiphon reboilers can be used in a wide range of operating pressures and temperatures. Therefore, they are used for about 70 % of all evaporation duties in chemical industry [2].

2. SETUP OF VERTICAL THERMOSIPHON REBOILERS

In *figure 1*, several setups for thermosiphon reboilers combined with a distillation column are shown.

Figure 1(A) depicts the standard setup. The vertical thermosiphon reboiler is connected to the column by a liquid feed line. Usually, a valve for controlling the liquid flow rate is installed in the inlet pipe. The liquid enters the heat exchanger at the bottom and is heated and partially evaporated inside the pipes. A vapor–liquid mixture leaves the reboiler through the exit line. The liquid circulation is driven by the difference in static pressure between the liquid in the inlet line and the partially evaporated fluid in the reboiler. No pumping is required for circulation in most services. Therefore, the design of thermosiphon reboilers has to take special care for a low pressure drop.

Generally, just 5 (inorganic liquids) to 20 (organic liquids) weight percent of the liquid is evaporated. Thus, the liquid circulates several times before complete evaporation. This ensures little fouling, high flow velocities and, in turn, high heat transfer rates.

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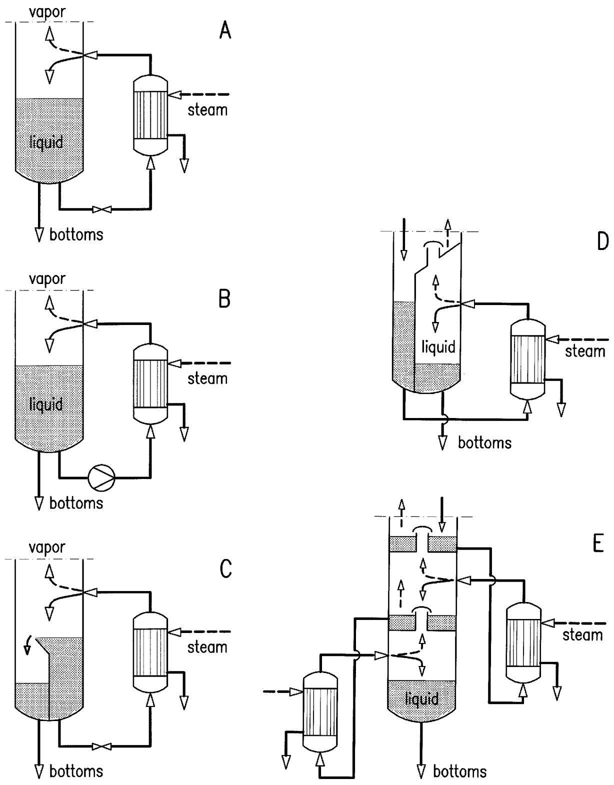

Figure 1. Setups of thermosiphon reboilers: (A) vertical thermosiphon reboiler, (B) forced circulation vertical thermosiphon reboiler, (C) vertical thermosiphon reboiler with fixed liquid head, (D) once-through vertical thermosiphon reboiler, (E) once-through naturally forced vertical thermosiphon reboiler.

Installing a pump in the inlet line leads to the forced circulation vertical thermosiphon reboiler shown in *figure 1(B)*. This setup can achieve higher heat transfer rates through higher liquid circulation rates especially at high vacuum operation, low liquid heads or small temperature differences between the heating medium and the liquid in the reboiler. For high vacuum services, when the pressure drop within the reboiler or the viscosity of the fluid is very high, this type of reboiler should be preferred [3].

The special design for the bottom of the column in *figure 1(C)* ensures a fixed liquid level feed to the reboiler even if the flow rate from the column varies.

A reboiler where the liquid from the column is heated only once is called a once-through vertical thermosiphon reboiler, see *figure 1(D)*. A short residence time of the liquid in the reboiler can be achieved with this design. However, just a small fraction of the liquid is evaporated.

A very sophisticated design that has the advantages of a forced circulation reboiler without the disadvantages of a pump (risk of break down or leakage) is shown in *figure 1(E)*. This once-through naturally forced vertical thermosiphon reboiler will be installed in distillation columns when a low boiling substance has to be separated from a high boiling mixture.

3. FUNDAMENTALS

The influence of the major operational and design parameters on heat flux and liquid circulation rate of thermosiphon reboilers will be discussed here.

In a thermosiphon reboiler, there exists a complex mutual interaction between two-phase flow and heat transfer. The heat transfer depends among others on the pressure, the vapor–liquid equilibrium, the flow rates and the system properties, while the two-phase flow is primarily influenced by the heat transfer rate and the pressure drop. The specific influence of all these parameters on the performance of thermosiphon reboilers will be discussed in detail.

In order to understand the response of the thermosiphon reboiler to a variation of the relevant parameters, it is helpful to divide the reboiler into two zones: a heating zone where the liquid is heated up to its boiling point and, above that, an evaporization zone where the liquid is partially evaporated by further heating as well as by pressure drop (flash). The principal mechanisms are shown in *figure 2(A)*. The heat transfer coefficient is much higher in the evaporization zone than in the heating zone. Therefore, changes of the length of these two zones have strong influence on the total heat transfer rate.

Figure 2(B) illustrates the principal temperature profile versus the tube length. The liquid entering the reboiler tubes has approximately the same temperature as the liquid in the bottom of the column. Due to the liquid head in the vertical inlet line the fluid is significantly subcooled at the reboiler entrance. Within the heating zone the temperature rises to the boiling point which depends significantly on the local liquid head. Boiling begins when the liquid has reached the local boiling temperature. Here, the heating zone ends and the evaporation zone begins. Within the evaporation zone the state of the liquid approximately follows the vapor pressure curve.

At atmospheric pressure the length of the heating zone is typically 20–50 % of the total tube length. It increases significantly with decreasing pressure. At high vacuum services the length of the heating zone approches 90 % or even more of tube length. Since just the evaporation zone drives the liquid circulation the circulation rate decreases drastically with decreasing pressure. Eventually, the liquid circulation breaks down.

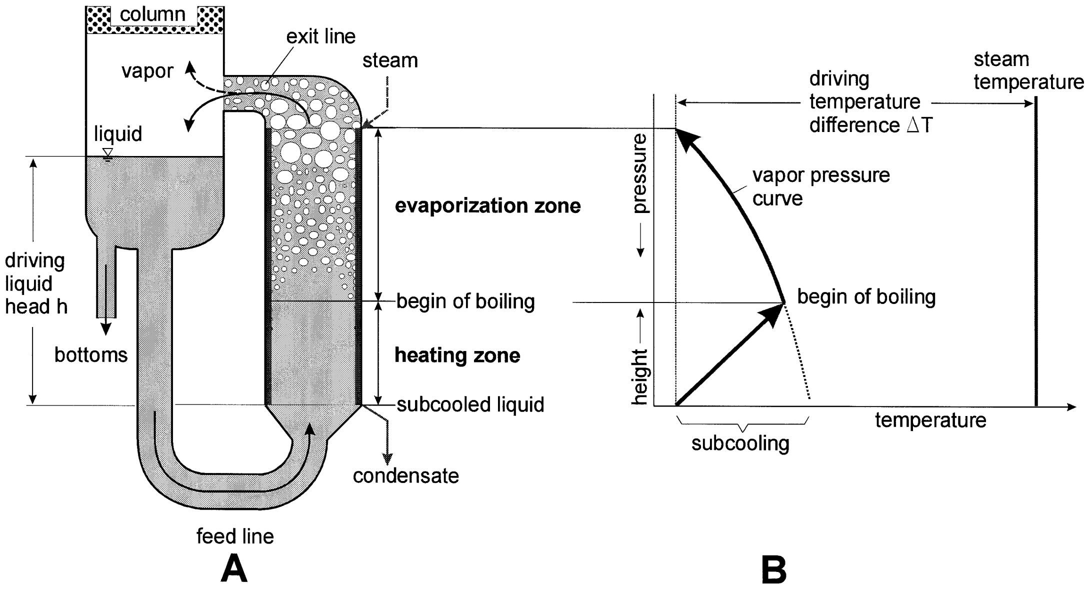

Figure 2. (A) Schematic of a vertical thermosiphon reboiler. (B) Characteristic temperature profile.

4. OPERATIONAL CHARACTERISTICS OF VERTICAL THERMOSIPHON REBOILERS

The following description of the operational characteristics of thermosiphon reboilers is based on an extensive experimental study of a single tube evaporator [4]. In this study the operational and design parameters have been varied in the range of technical relevance. Furthermore, a novel model has been developed for the simulation of the operational characteristics of thermosiphon reboilers [4]. The model considers two heat transfer zones only, a heating zone and, above that, an evaporation zone. The heat transfer coefficients and the mass flow rates are modelled just in the middle of each zone by published correlations, i.e., Blasius, Rouhani and Axelson, Friedel, Techo, Isahenko, Dittus and Boelter, Liu and Winterton, [5, 6]. This very simple model describes the operational characteristics of thermosiphon reboilers with sufficient accuracy.

4.1. Influence of driving temperature difference

Figure 3 shows the influence of the driving temperature difference (see *figure 2(B)*) on the specific overall heat flux. At low temperature differences the specific overall heat flux rises steeply with increasing temperature differences. Since more liquid is evaporated, the fluid velocity and, in turn, the heat transfer coefficients rise what reduces the length of the heating zone. As the length of the evaporization zone with enhanced heat transfer increases, the overall heat flux rises significantly.

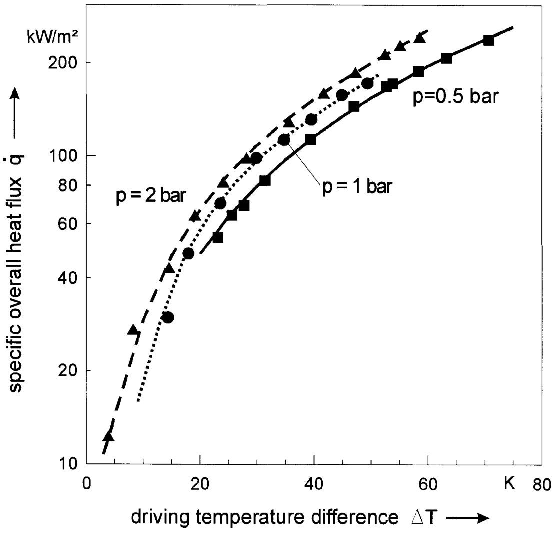

Figure 3. Specific overall heat flux versus driving temperature difference. ●, ■, ▲: experimental data. Lines: simulation with own model.

At higher driving temperature differences the increase of the heat transfer rate slows down a little. The liquid circulation through the tubes reaches its maximum at a temperature difference of about 20–30 K and decreases thereafter, in dependence on the pipe diameter and length. Also, the growth in length of the vaporization zone becomes smaller.

A dependence of the overall heat flux on the operating pressure of the thermosiphon reboiler is observed. The heat flux rises with system pressure. Besides the influence of the pressure on the system properties, this effect mainly depends on the smaller subcooling of the liquid at high pressures. This mechanism will be described in detail in the next section.

The data for the mass flow density are plotted versus the driving temperature difference in *figure 4*. The lines represent the simulation, the dots the experimental data. The mass flow density in a thermosiphon reboiler rises sharply at small driving temperature differences. It usually reaches its maximum at about 20 K temperature difference and decreases thereafter. This characteristic behavior has been observed in all experiments.

At small driving temperature differences, there exists just a small density difference between the liquid in the feed line and the two phase mixture in the reboiler. Thus, the driving force for the natural circulation is small. A rise of the temperature difference will evaporate more liquid and, in turn, enhance the liquid circulation. However, the pressure drop increases significantly at higher evaporation rates what reduces the circulation rates. At a driving temperature difference of 20–30 K the increase in driving force for natural circulation is compensated for by the rising pressure drop. At higher driving temperature differences the mass flow density decreases since the pressure drop becomes the dominant mechanism.

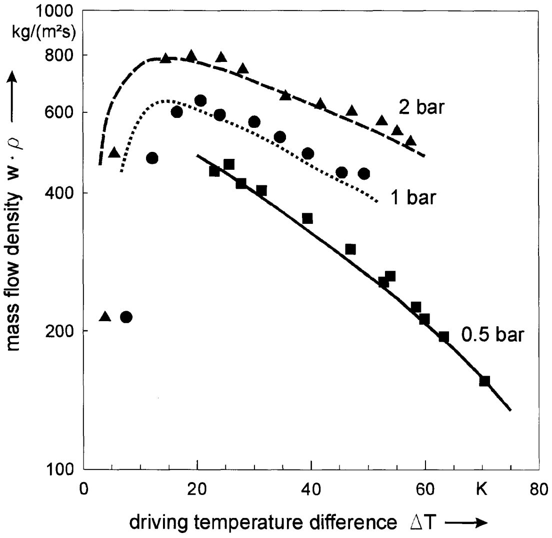

Figure 4. Mass flow density versus driving temperature difference. ●, ■, ▲: experimental data. Lines: simulation with own model.

There is a risk of flow instabilities (oscillations) and, eventually, of burnout at very large driving temperature differences. Heavy deviations of the average flow rates were observed in oscillationary flow. Closing the throttling valve in the inlet line is an effective means for suppressing these unwanted oscillations. The risk of the development of oscillations is higher at low liquid heads and low operating pressures. Oscillations are more often observed at operations with organic liquids than with inorganic liquids (e.g., water). Burnout is caused by film boiling at the upper end of the pipes at very high driving temperature differences. Burnout must be avoided since the heat transfer to a vapor is generally rather poor. Therefore, rising the driving temperature difference above a critical value will lead to a lower vapor generation. Thermosiphon reboilers show an inverse operation characteristic in this range of operation [5].

4.2. Influence of operating pressure

The operating pressure strongly influences the performance of a thermosiphon reboiler. At low operating pressures the influence of the subcooling of the liquid at the reboiler inlet is of major importance.

This is explained for a thermosiphon reboiler of 4 m heated pipe length operated with water. At a pressure of 0.1 bar in the bottom of the column, the pressure due to the liquid head in the feed line is 0.5 bar. Hence, the liquid is approximately 35 K subcooled. If the same reboiler is operated at 3 bar, the pressure at the inlet is 3.4 bar what refers to a subcooling of 4 K only. Thus, at low pressures an increase of the pressure is decisive for the subcooling and, in turn, for the heat transfer rate. Adversely at high pressures, the subcooling of the liquid is very low. The heating zone where the liquid is warmed up to the boiling temperature is much shorter. Furthermore, the increased vapor content in the pipe causes a larger density difference and, in turn, a higher circulation rate. This increases the length of the evaporization zone. Since the heat transfer coefficient is significantly higher in the evaporization zone than in the heating zone, higher operating pressures enhance the heat transfer rates.

Figure 5 shows the influence of the operating pressure on the specific overall heat flux $\dot{q}$ (left ordinate) and the

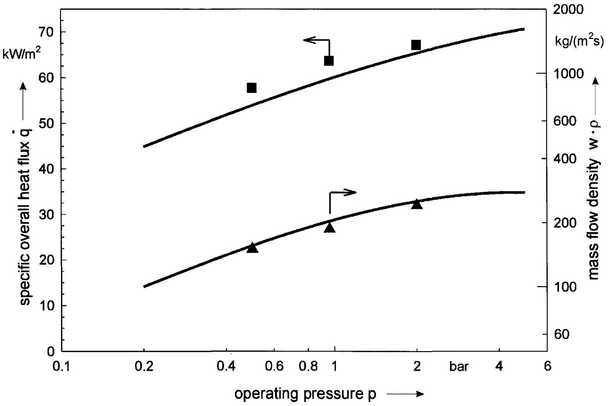

Figure 5. Influence of the operating pressure on the specific overall heat flux (left ordinate) and the mass flow density (right ordinate). ■, ▲: experimental data. Lines: simulation with own model.

mass flow density $w \cdot \rho$ (right ordinate). The experimental data have been collected with toluene in a vertical thermosiphon reboiler with tubes of 50 mm in diameter and 2 m in length. The liquid head was 75 % of the tube length and the driving temperature difference was 15 K.

The heat flux as well as the mass flow density rate increase with rising operating pressure due to the mechanisms described above. Similar results have been published by [7–9].

4.3. Influence of pipe diameter

The influence of pipe diameter on the specific overall heat flux and the mass flow density is illustrated in *figure 6*. While the specific overall heat transfer rate decreases with increasing pipe diameter, the heat transfer rate per tube rises. With increasing pipe diameter the ratio of heat transfer area to heated pipe volume becomes smaller. Thus, the heating zone is longer and the heat flux smaller. In other words, smaller pipes are more effective in terms of specific heat flux than larger ones.

The specific mass flow, i.e., the mass flux related to the pipe cross section, increases with increasing pipe diameter. There are two major reasons for this:

- The friction caused by the fluid flow is smaller in bigger pipes.
- The pressure drop caused by acceleration is smaller in larger pipes due to a smaller vapor content.

Both mechanisms enhance the mass flow density. Similar results as plotted in *figure 6* have been observed at several operating pressures, fluids, pipe lengths and liquid heads in the inlet line.

4.4. Influence of pipe length

The effect of pipe length on the specific overall heat flux and the mass flow density is illustrated in *figure 7*. The longer the pipes the more liquid is evaporated. This leads to a higher mass flow rate. However, due to the higher content of vapor the pressure drop rises even more. Therefore, the overall mass flow density decreases slightly in longer pipes.

The pipe length has little influence on the ratio of the length of the heating and the evaporization zone provided the pipes are longer than 1 m. Hence, the specific overall heat fluxes of pipes of different length are very similar. This is because the pressure drop in the

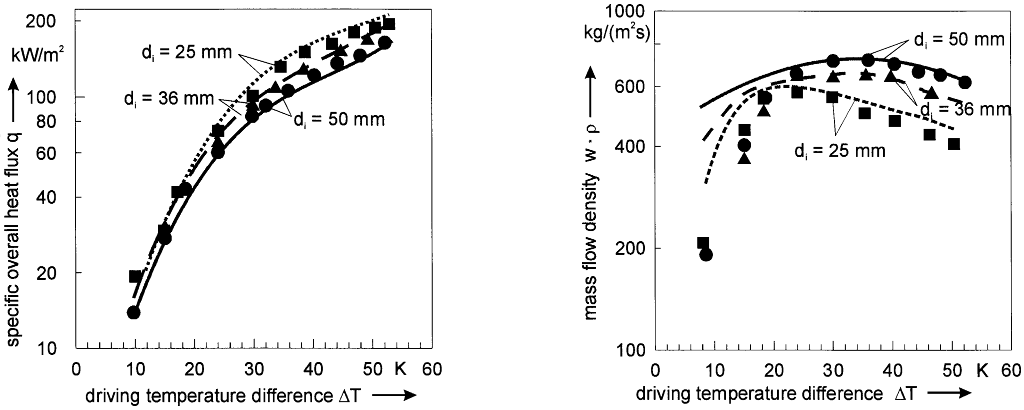

Figure 6. Influence of the pipe diameter on the specific overall heat flux (left) and the mass flow density (right). ●, ■, ▲: experimental data. Lines: simulation with own model.

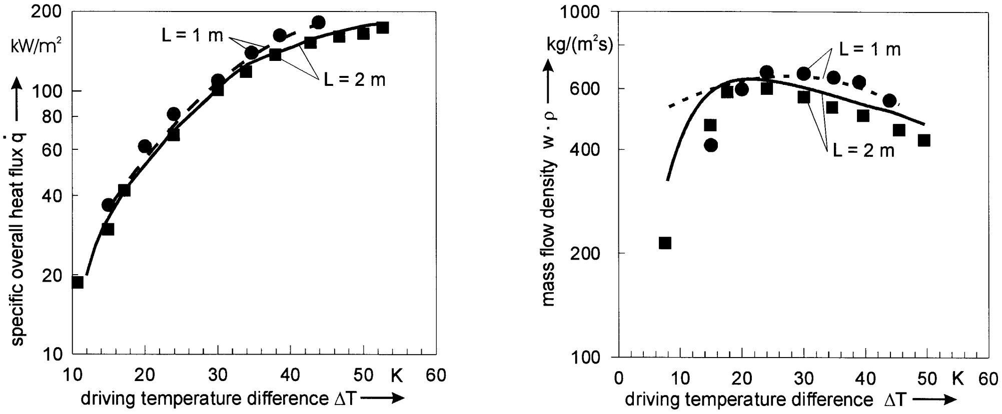

Figure 7. Influence of the pipe length on the specific overall heat flux (left) and the mass flow density (right). ●, ■: experimental data. Lines: simulation with own model.

exit line is fairly independent of the pipe length and has bigger influence on the overall pressure drop at shorter pipes. For pipes shorter than 1 m the experiments showed a strong influence of the pipe length on the mass flow density rate while there was almost no influence on the specific overall heat flux.

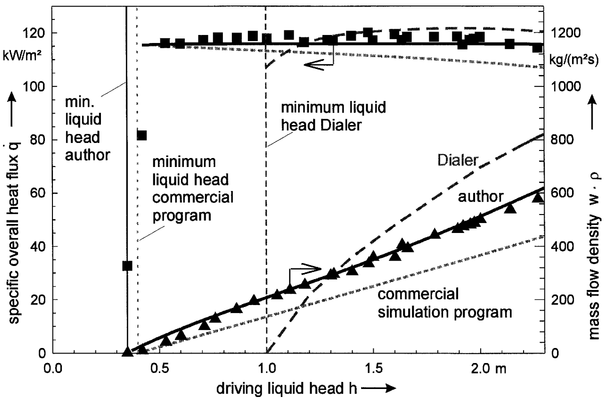

Figure 8. Influence of the liquid head on the specific overall heat flux (left ordinate) and the mass flow density (right ordinate). ■: experimental data for the specific heat flux, ▲: experimental data for the specific circulation rate. Lines: results of three different simulation programs.

4.5. Influence of driving liquid head

The driving liquid head is a very important operational parameter of a thermosiphon reboiler since it can be manipulated very easily.

Figure 8 shows the dependence of the specific overall heat flux (left ordinate) and of the mass flow density (right ordinate) on the driving liquid head.

The mass flow density is, above a critical value, approximately a linear function of the driving liquid head. The higher the liquid head the larger is the mass flow density. Below a critical value of the driving liquid head the liquid circulation breaks down and, in turn, the heat transfer is very poor.

Astonishing is the fact that the heat transfer rate is approximately independent of the driving liquid heads. There are two competing mechanisms that are inversely changed by a variation of the driving liquid head. At low driving heads, the heat transfer coefficients are generally low due to the low circulation rate but the evaporation zone with enhanced heat transfer is long. Thus, the overall heat transfer coefficient is quite high even at low driving liquid heads.

At high driving liquid heads, the heat transfer coefficients are higher in both the heating zone and the evaporation zone due to the higher circulation rate. However, the length of the evaporation zone with enhanced heat transfer is shorter what reduces the mean heat transfer coefficient of the reboiler. As can be seen from *figure 8*, the specific overall heat flux is nearly independent of the driving liquid head.

Thus, increase of the heat transfer coefficient by an increased driving head is compensated for by a reduction of the length of the evaporation zone. This holds for the evaporation of water or similar systems at a pressure of 1 bar or higher. At low system pressures, however, especially in vacuum services, the behaviour of the thermosiphon reboiler is different due to the short length of the evaporation zone.

Besides the experimental data, *figure 8* shows the influence of the liquid head on the heat transfer and the circulation rate as predicted by three different models. All three models predict only a small effect of the liquid head on heat transfer rates (upper lines in *figure 8*). However, the influence on the circulation rate is very different in the three models.

The own experiments and data from literature showed that thermosiphon reboilers operated at ambient or higher pressures show best performance at driving liquid heads of 80–100 % of the pipe length while reboilers operated in vacuum conditions work best with liquid heads between 50 and 70 % of the pipe length [10, 11].

5. CONCLUSIONS

In a thermosiphon reboiler, there exists a complex mutual interaction between heat transfer and two-phase flow. Decisive for the operational characteristic of a thermosiphon reboiler is the length of the heating and the evaporation zone, respectively. Since the values of the heat transfer coefficients are much higher in the evaporation than in the heating zone the overall heat transfer rate of the reboiler is governed by the length of the evaporation zone. The key point for the modelling of the operational characteristics of thermosiphon reboilers is the correct description of the liquid circulation rate that depends significantly on the pressure drop and the vapor content in the evaporator.

REFERENCES

[1] Love D.L., No hassle reboiler selection, Hydrocarbon Processing (1992) 41–47.

[2] Sloley A.W., Properly design thermosyphon reboilers, Chem. Engrg. Progr. (1997) 52–64.

[3] Kister H.Z., Distillation Operation, McGraw-Hill, New York, 1990.

[4] Arneth S., Dimensionierung und Betriebsverhalten von Naturumlaufverdampfern, Hieronymus Verlag, München, 1999.

[5] VDI-Wärmeatlas, Verein Deutscher Ingenieure, VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC), VDI-Verlag, Düsseldorf, 1995.

[6] Hewitt G.F., Heat Exchanger Design Handbook, Begell House, New York, Wallingford, 1998.

[7] Kirschbaum E., Einflußdes Rohrdurchmessers und der Rohrlänge auf die Leistung von Verdampfungsapparaten mit Selbstumlauf, Chem. Ing. Tech. 34 (1962) 183–192.

[8] Leniger H.A., Veldstra J., Wärmedurchgang in einem senkrechten Verdampferrohr bei natürlichem Umlauf, Chem. Ing. Tech. 34 (1962) 21–26.

[9] Dialer K., Die Wärmeübertragung beim Naturumlaufverdampfer, ADAG Administration & Druck AG, Zürich, 1983.

[10] Harrison M.E., France J.J., Troubleshooting distillation columns, Chem. Engrg. (1989) 130–137.

[11] Shah G.C., Troubleshooting reboiler systems, Chem. Engrg. Progr. 75 (1979) 53–58.