Use of Wire Matrix Inserts in Thermosiphon Reboilers in the Lower Operating Range

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Turbulators are applied to increase the thermal efficiency of heat transfer units. The additional pressure drop can be challenging for the self-circulation of thermosiphon reboilers. Thus, the effects of hiTRAN®-wire matrix inserts for the boiling of water and a water/glycerol mixture were investigated herein, using the performance of a thermosiphon reboiler with plain tubes as a reference. The reboiler was operated at sub-atmospheric pressures, small driving temperature differences, and under flooded conditions. Favorable and unfavorable operating conditions for using inserts were specified. Especially for the water/glycerol mixture, significant improvements of self-circulation and heat transfer up to six times compared to the plain tube reference were observed, allowing an operation of thermosiphon reboilers at smaller driving temperature differences under sub-atmospheric pressures.

Keywords: Heat transfer enhancement, Operating limit, Thermosiphon reboiler

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1 Introduction

Thermosiphon reboilers are operated pumpless by self-circulation. The self-circulation is driven by the density difference between subcooled liquid flow at the inlet and partially evaporated flow at the outlet of the reboiler. Pumpless operation reduces mechanical stress on the product as well as investment and operating costs. Additional advantages of thermosiphon reboilers are a high heat transfer rate, a low fouling tendency, and a simple setup. Thus, they are one of the most frequently used reboiler types in process industries. Vertical thermosiphon reboilers, in particular, serve about 70 % of all evaporation duties in the chemical industry [1]. However, there is a dearth of data and literature available for the operation of thermosiphon reboilers in the lower operating range, especially at sub-atmospheric pressure and with small driving temperature difference.

Operating thermosiphon reboilers at this lower operating range, sensible products can be evaporated with minimal mechanical and thermal stress. Moreover, thermosiphon reboilers operated under these conditions can be used more efficiently in heat integration as heat sinks. However, their performance can be limited at the lower operating range due to larger subcooling at the reboiler inlet and the reduction of flowability. A larger subcooling leads to a longer heating zone with decreased heat transfer rates. The length of the heating zone is typically 20 %–50 % of the total tube length; while under low pressures, evaporation takes place in only 10 % or less of the tube length [1]. Intense evaporation is crucial for adequate self-circulation. To maintain it at a stable level, a continuous and sufficient generation of vapor is required, which defines suitable operating parameters. Boiling with self-circulation can be challenging if the reboilers are operated with small driving temperature differences, low total pressures, low static heads or evaporating fluids with disadvantageous properties such as high viscosities. Unstable flow or breakdowns can take place if the operating conditions are chosen improperly.

To positively influence the performance of thermosiphon reboilers in the lower operating range, two possibilities are available: operating at the optimal static liquid head and modifying the heat transfer area with enhancement techniques. At a static liquid head of 110 %, a thermosiphon reboiler shows significantly improved self-circulation with a negligibly reduced heat flux in comparison to other static liquid heads [1–4]. This submerged condition stabilizes operation in the lower operation range. For the second option the following heat transfer enhancement techniques were investigated for thermosiphon reboilers:

- swirl-flow devices: wire matrix inserts [4–7], static mixer inserts, twisted tape inserts, and helically coiled wire inserts [6],
- extended surfaces: finned tubes [5],
- treated surfaces: hydrophobic nanoparticle coated tubes [8] and
- displaced enhancement devices: pillow plates [3, 9].

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Among these, wire matrix inserts show much potential in improving thermosiphon reboilers at low operating pressures and small driving temperature differences [5]. hiTRAN®-wire matrix inserts consist of woven wire loops set in a helical arrangement [10]. As a type of turbulators, they force intense mixing by inducing turbulence in pipe flows, resulting in a change in velocity profile with higher velocities near the wall [11]. Furthermore, they provide more nucleation points, and support bubble generation and detachment in subcooled boiling [4]. The improvement is based on the enhanced single-phase heat transfer and the extended evaporation zone [7].

Simulations conducted by Nasr and Tahmasbi [6] showed a reduction of the heating zone length by 33 % with low density and by 59 % with high density wire matrix inserts. Reddy et al. [7] demonstrated that for a driving temperature difference of 33 K a heat load enhancement of 4 % was possible, while for \( \Delta T = 8 \) K an enhancement of 12.9 % could be achieved. Additionally, the use of inserts at an operating pressure of 100 mbar resulted in a 42 % higher overall heat transfer coefficient and a reduction of the heating zone length from 81 % to 55 %. In these two simulations, the insert length was set as equal to the heating zone length based on simulation without inserts.

Scholl and Brahim [4] obtained experimental results using inserts in the lower half of the tube and compared these to results of a plain tube as well as inserts over the total length of the tube with various loop volume densities. A half-length insert showed a significantly better thermal performance for the investigated conditions with a small driving temperature difference and a low static liquid head. Among the full-length inserts, the one with 3 % loop volume fraction provided the best performance. By using this type of insert for the total tube length, Hammerschmidt and Scholl [5] reported 10 % tube-side heat transfer enhancement for water and 2.5 times enhancement for a water/glycerol mixture.

Therefore, these studies determined conditions that provided most benefits at the lower range of operation. In the upper range of operation, with a strong and stable self-circulation, the subcooling of the inlet flow is usually small and the potential improvement of the single-phase heat transfer is limited. In addition, a strong self-circulation is available in the upper operating range with a corresponding large pressure drop. Thus, the limited improvement of single-phase heat transfer is needed to overcome the increased pressure drop. Overall, no resulting aggregate benefit appears to be possible [4]. Thus, this work aims to provide a systematic investigation of an intensified thermosiphon reboiler focusing on the lower operating range.

## 2 Experimental Setup and Assessment

### 2.1 Setup and Operation

The test rig as shown in Fig. 1 was constructed by Hammerschmidt [5] for a single tube thermosiphon reboiler and recommissioned to three tubes with the same reboiler tube diameter and length. The reboiler tube geometry was \( d_s \times L = 20 \times 2 \times 1500 \) mm with a tube pitch of 25 mm. The reboiler was steam-heated as a vertical shell and tube heat exchanger E1 made of stainless-steel SS 1.4571. Four wire resistance thermometers (TMH Pt 100/A, tolerance \( \pm 0.15 \) K) and pressure transmitters (Keller PAA35XHTC with a measuring range of 0–2 bar and a precision of 0.5 % FS) were installed with tapping points 6 mm below and 6 mm above the reboiler tubes.

The boiling fluid flowed through the exit line into the vapor-liquid separator D1, which was heated by thermal oil in a jacket to minimize heat loss. The temperature of vapor exiting the separator \( T_{\text{top}} \) the bottom temperature \( T_{\text{bottom}} \) and the system pressure \( p_{\text{sys}} \) were determined by resistance thermometers TIR109 and TIR110 and a pressure transmitter PIR206 (Keller PAA35XHTC with a measuring range of 0–2 bar and a precision of 0.5 % FS), respectively. The operating pressure at the product side was controlled via vacuum pump P3 (Vacuubrand PC 3000). The liquid level in the vapor-liquid separator was measured by a float switch LIR210 (TORRIX-E). The static liquid head \( h_\text{s}^* \) specifies the liquid level as the ratio of the distance \( h \), as measured between the liquid head in separator D1 and the inlet of reboiler tubes, to the length of the reboiler tubes \( L_{RT} \), as per Eq. (1).

\[
h_\text{s}^* = \frac{h}{L_{RT}} \cdot 100\%
\]  

The exit line was designed towards small pressure loss by means of a short pipe length and a smooth pipe elbow. It is located between the static liquid head of 103.8 % and 106.5 %. At \( h_\text{s}^* > 106.5 \) %, the exit line and the reboiler were completely submerged. The circulating mass flow \( m_{\text{circ}} \) FIR208 and density DIR209 were determined by a Coriolis flow meter F1 (Promass 80F25-AD2SAP5EAAA.A8).

The distillate exiting the vapor-liquid separator was condensed with cooling water in a glass heat exchanger E3. The condensate was collected and weighed (Sartorius SIWSDCP-1-35-H) in D2 to determine the distillate mass flow \( m_{\text{d2}} \). After weighing, the condensate was preheated electrically (E4) and pumped back to the vapor-liquid separator via P2 (Prominent Gamma L).

The reboiler tubes were heated by condensing steam on the shell side, supplied by a boiling thermostat E2 (gwk VACUTHERM v016). The thermostat was operated with water, which allowed a heating temperature range of 46°C–96°C and a maximum heat duty of 6 kW. The temperature at the shell-side inlet and outlet as well as the pressure in the middle of the shell were measured by resistance
thermometers TIR106 and TIR107 and a pressure transmitter PIR205 (Keller PAA35XHTC with a measuring range of 0–1 bar and a precision of 0.5 % FS), respectively. The steam condensing on the outer surface of the reboiler tubes was collected in tank D3. Unlike the setup of Hammerschmidt [5], the mass flow of the condensing steam was quantified by a differential pressure transducer PDIR221 (BD SENSORS DPT 200, measure range 60 mbar ± 0.075 % FSO), which is less affected by vibration or trickle. At one side of its membrane, the tube was completely filled with water ensuring a constant static pressure, at the other side the pressure is determined by the amount of condensate collected in D3, therefore indicating the liquid level in the tank. The level was plotted over time and a condensate mass flow derived. By reaching a threshold of differential pressure, the solenoid-operated valve V15 opened and allowed the condensate to flow back into the boiling thermostat. The subcooling of the steam was determined via a resistance thermometer TIR108.

The data acquisition and process control were carried out via LabVIEW software. Measurements were taken, starting from when the circulation flow rate and temperatures in vapor-liquid separator D1 and in the reboiler were at steady state. The averaged values recorded over a period of 30 min were taken as primary experimental data, with the exception of circulation mass flow, for which the median value was used so as to be less affected by circulation fluctuation.

2.2 Operation Condition

The varied operation parameters are listed in Tab. 1. At the product side, water and a water/glycerol mixture with a glycerol mole fraction of $x_{\text{gly}} = (0.33 ± 0.02) \text{ molgly/moltot}^{-1}$ were investigated. Water was used to simulate thermosiphon reboilers used at the bottom of the rectification column, while the water/glycerol mixture acted as a model mixture for the separation of wide boiling mixtures and systems with elevated viscosity [4]. The physical properties: densities; viscosities; thermal capacities and the enthalpy of evaporation for pure materials and mixtures were calculated according to [12].

Specifically, this investigation focused on operating thermosiphon reboilers under vacuum conditions and at small driving temperature differences. The results under a submerged condition with static liquid heads $\geq 106\%$ are shown here, since a larger potential for stable operation at low driving forces was expected.
The inlet velocity was calculated with Eq. (2).

\[ u_{in} = \frac{m_{circ}}{\rho_{in} A_{in}} \]  

(2)

The use of inserts in the reboiler tubes was also studied. For those experiments, a hiTRAN®-wire matrix turbulator with a loop volume fraction of 3% and a length of 600 mm (produced by CALGAVIN Ltd) was installed in each plain tube with their loops leaning against the flow direction. The inserts were installed in the inlet section of the reboiler, resulting in 40% of the reboiler tube length. In this section, the working fluid is usually subcooled. Thus, the insert was primarily used to intensify the single-phase heat transfer and the boiling area was either not or less affected at all.

### 2.3 Calculation of the Fluid Dynamic and Thermal Performance

The fluid dynamics of thermosiphon boiling was characterized by the tube inlet velocity and the Reynolds number. The inlet velocity was calculated with Eq. (2).

\[ u_{in} = \frac{m_{circ}}{\rho_{in} A_{in}} \]  

(2)

The propagation of uncertainty for inlet velocity was calculated using Eq. (3) and plotted as an error bar showing the fluctuation of the circulation flow. For the deviation of circulation rate and inlet temperature, the median absolute deviation and the standard deviation of the measured values were used, respectively. The deviation of glycerol mole fractions was 0.02 molGlymoltot⁻¹. A deviation of 1% was calculated for the inner diameter.

\[ \Delta u_{in} = \left( \left( \frac{\delta u_{in}}{u_{in}} \Delta m_{irc} \right)^2 + \left( \frac{\delta \rho_{in}}{\rho_{in}} \Delta T_{in} \right)^2 \right)^{1/2} \]  

(3)

Moreover, the Reynolds number was plotted alongside the inlet velocity presenting the flow regime. For this purpose, the physical properties ratio \( \rho / \eta \) was averaged due to temperature variation shown in each diagram.

\[ Re = u_{in} d \left( \frac{\rho}{\eta} \right) \]  

(4)

| Test medium | Water | Water/glycerol mixture with \( x_{Gly} = 0.33 \) molGlymoltot⁻¹ |
|-------------|-------|-------------------------------------------------|
| Static liquid head [%] | \( 110 \leq h_s \leq 120 \) | |
| Operating pressure [mbar] | \( 100 \leq p \leq 400 \) | \( 100 \leq p \leq 300 \) |
| Driving temperature difference [K] | \( 5 \leq \Delta T \leq 12 \) | \( 7 \leq \Delta T \leq 19 \) |
| Reboiler tube configuration | Plain tube, tube with insert | |

Table 1. Variation of the operating parameters.

The driving temperature difference specifies the thermal driving force between shell side and product side. Different definitions are used in the literature or in practical application, depending on the focus of the work or availability of experimental data. While a difference in the actual definitions might not be significant in general terms, it becomes crucial when looking at small absolute values of \( \Delta T \) – as in the present case. Four typical definitions are given in the legend of Fig. 2. Exemplary values were calculated from an identical set of experiments at \( p_{Gly} = 200 \) mbar with a water/glycerol mixture and are shown in Fig. 2 with varying shell-side temperature.

The temperature difference referring to the reboiler outlet directly reflects the situation of the boiling two-phase mixture as it exits. However, it is always lower than the other definitions since the temperature decreases in the exit line. Due to the limited instrumentation at this position, the definition referring to the outlet temperature was rarely used. At small driving temperature differences, only a minor self-circulation was induced resulting in subcooling in the vapor-liquid separator. Consequently, this condition led to the occurrence of large differences of up to 5 K when using different definitions, cf. Fig. 2. Operating at higher shell-side temperature, the definitions referring to \( T_{top} \) and \( T_{in} \) showed identical results. Using \( T_{bottom} \), \( \Delta T \) was about 1 K higher than the last two definitions.

Most frequently, the temperature at the reboiler inlet was also used for simulation of thermosiphon reboilers [3, 5, 13, 14]. It represents the temperature at which single phase heating of the tube side flow starts. Thus, the definition of driving temperature difference referring to the reboiler inlet was used in this work, see Eq. (5).

\[ \Delta T = T_{shell} - T_{in} \]  

(5)

The heat flux at the product side was used to quantify the thermal performance of thermosiphon reboiler. Additionally, heat transfer enhancement at the tube side was investigated. Consequently, the heat flux expressed as heat flow per tube-side heat transfer area was used throughout this study, see Eq. (6).

\[ \dot{q} = \frac{Q}{A_{ht}} = \frac{\dot{Q}}{\pi dL} \]  

(6)

The system boundary for heat balance is shown in Fig. 3. It consists of the heat flow of the circulation flow entering and leaving the reboiler, the vapor leaving the vapor-liquid separator, the feed entering the vapor-liquid separator, and the heat loss, as presented in Eq. (7).
The heat flow of the reboiler is defined as per Eq. (8).

Accompanying this, the heat flows of vapor leaving the vapor-liquid separator $Q_{\text{dist}}$ and the feed entering the vapor-liquid separator $Q_{\text{feed}}$ are given in Eq. (9) and (10).

\[
Q = Q_{\text{circ, out}} - Q_{\text{circ, in}} = Q_{\text{dist}} - Q_{\text{feed}} + Q_{\text{hl}} \\
\dot{Q}_{\text{dist}} = \dot{m}_{\text{dist}} c_p (T_{\text{top}} + \Delta h_v) \\
\dot{Q}_{\text{feed}} = \dot{m}_{\text{feed}} c_p T_{\text{feed}}
\]  

(7) 

(8) 

(9) 

(10)

Figure 2. Definitions of driving temperature difference and its exemplary values calculated from an identical set of experiments at $P_{\text{sys}} = 200$ mbar with a water/glycerol mixture.

Figure 3. Heat balance.

\[
0 = \dot{Q}_{\text{circ, out}} - \dot{Q}_{\text{circ, in}} - \dot{Q}_{\text{dist}} + \dot{Q}_{\text{feed}} - \dot{Q}_{\text{hl}}
\]

As stated above, the extent of the different heat losses also varied with operating conditions which was especially relevant at the lower operating limit.

Pertinently, the circulation ratio is a key variable of boiler/reboiler design [16–18]. It combines the fluid dynamic and thermal performance, and is defined as the mass flow rate of the liquid entering the reboiler tubes divided by the mass flow rate of the vapor at the reboiler outlet. In the field of power generation, Teir and Kulla [17] reported a circulation ratio of 5–100 for natural circulation boilers depending on the system pressure, where low-pressure boilers generally had higher ratios. Thermosiphon reboilers are typically operated at circulation ratios ranging between 6 and 14 [12]. In this work, the circulation ratio was calculated with the circulation flow rate $\dot{m}_{\text{circ}}$ and the distillate mass flow $\dot{m}_{\text{dist}}$ exiting the vapor-liquid separator, see Eq. (12).

\[
C = \frac{\dot{m}_{\text{circ}}}{\dot{m}_{\text{dist}}}
\]

(11)

(12)

3 Results

In the following, the evaporation behavior of water and a water/glycerol mixture within the thermosiphon reboiler is presented for varying operating parameters. The overall heat flux $\dot{q}$ represents the thermal performance, while reboiler tube inlet velocity $u_{\text{in}}$ and Reynolds number give an assessment of the fluid dynamic performance. The thermal and fluid dynamic performance are then jointly discussed based on the circulation ratio. The calculation methods of the parameters used were introduced in Sect. 2.3.

3.1 Evaporation of Water in a Thermosiphon Reboiler

Since the fluid dynamic and thermal performance of thermosiphon reboilers are closely coupled, they are presented
in Fig. 4 and 5 for a direct comparison. Open circles and filled squares depict the experimental results obtained with plain tubes and with hiTRAN®-inserts, respectively. Operating pressures were at 100 mbar \( \leq p_{sys} \leq 400 \) mbar with a constant static liquid head of 110 %.

**Figure 4.** Inlet velocity \( u_{in} \), Reynolds number \( Re \) and heat flux \( q \) vs. driving temperature difference \( \Delta T \) for water at operating pressures of 100 mbar and 200 mbar with plain tubes (open circles) and with inserts (filled squares).

**Figure 5.** Inlet velocity \( u_{in} \), Reynolds number \( Re \) and heat flux \( q \) vs. driving temperature difference \( \Delta T \) for water at operating pressures of 300 mbar and 400 mbar with plain tubes (open circles) and with inserts (filled squares). The error bars of inlet velocity show the propagation of uncertainty.

At an operating pressure of 100 mbar, the use of inserts made no significant difference in the fluid dynamic performance, cf. Fig. 4a. In both series of experiments, the inlet velocity rose slightly with an increasing driving temperature difference while the heat flux showed a linear increase with the driving temperature difference, cf. Fig. 4b. The gradient was steeper when using inserts indicating a better heat transfer up to 30 %. Therefore, enhancement to heat transfer via inserts was observed. Although the thermal performance is coupled with the fluid dynamic, the use of inserts here brought no improvement to the observed natural circulation. This was due to the additional pressure drop caused by inserts, which suppressed the natural circulation. Overall, the improvement due to heat transfer enhancement compensated for the disadvantage of the additional pressure drop, so the inlet velocity turned out to be the same as recorded for plain tubes.

Increasing the operating pressure to 200 mbar yielded results that were similar to 100 mbar as no difference in inlet velocities were observed along with 30 % improvement of heat transfer, cf. Fig. 4c and 4d. However, an extension of the operating range was observed at 200 mbar: starting at a driving temperature difference of 5 K, a stable circulation was maintained. At this pressure, Hammerschmidt [2] showed significant heat flux enhancement up to 7 times by using the insert in a single-tube thermosiphon reboiler. In his work, the same type of wire matrix insert ranged over the total length of reboiler tube and was therefore more beneficial for the current case, since a long single-phase zone was anticipated at the lowest operation range.

Significant differences with and without inserts were seen when increasing the operating pressure to 300 mbar, cf. Fig. 5a and 5b. The experiments without inserts showed an abrupt increase of inlet velocity and heat flux at a driving temperature difference of 7 K. At \( \Delta T < 7 \) K, the inlet velocity remained similar. This could indicate a transition status between two fluid dynamic operating regimes. This observation could relate to the Ledinegg instability [19], which allows two operating points at identical operating conditions: one at a lower flow rate with a relatively large vapor fraction and the other at a higher flow rate with a small vapor fraction. It is unknown which operating point occurs, but only the second one is stable and resistant to disturbance [19]. Regarding the Reynolds number, it corresponds to the change in circulation flow from laminar to turbulent. Thus, the heat transfer was improved, but, again, the pressure drop was larger. This increased pressure drop could in turn decelerate the natural circulation and lead to flow instabilities. Moreover, the inlet velocities at temperature differences of \( \Delta T > 7 \) K were much higher than those at lower operating pressures, but the overall increase with \( \Delta T \) remained similar. This could indicate a transition from nucleate boiling to flow boiling. The maximum inlet velocity of 0.2 m s\(^{-1}\) was achieved at \( \Delta T = 10 \) K. With inserts, a maximum inlet velocity of only half of the previous figure was reached at \( \Delta T = 11 \) K and no discernible leap was determined in inlet velocity. It showed similar tendencies with regard to the temperature difference as that of the experiments without inserts at \( \Delta T < 7 \) K. The heat transfer showed similar behavior as coupled with fluid...
dynamic. At $\Delta T \geq 7$ K, significantly higher heat fluxes up to 16 kW m$^{-2}$ were transferred in plain tubes, whereas the thermal behavior at small temperature differences remained at the same level as the inserted tubes.

Operating the reboiler with plain tubes at a total pressure of 400 mbar resulted in an inlet velocity of 0.15 m s$^{-1}$ and turbulent flow conditions at a minimum temperature difference of 5 K, see Fig. 5c. No substantial leap was seen, and it can be assumed that the threshold of the lower operating level, which was observed in results at 100 mbar $\leq P_{BA} \leq 300$ mbar with $u_{in} \leq 0.1$ m s$^{-1}$, was already exceeded at $\Delta T = 5$ K. The maximum inlet flow and the maximum heat flux of all experiments, achieved at $\Delta T = 10$ K, were 0.24 m s$^{-1}$ and 17 kW m$^{-2}$, respectively. Conversely, boiling with tube inserts at temperature differences below 9 K showed similar fluid dynamic and thermal behavior like those at lower operating pressures, see Fig. 5c and 5d. At $\Delta T = 9.5$ K, a significant leap was identified in the inlet velocity as well as the heat flux. Compared to plain tubes, the inlet velocity was still lower, but the heat flux was similar. Once more, this confirms the inhibiting effect of inserts during the heating of a subcooled fluid.

This indicates that the use of hiTRAN$^\circledR$-inserts for boiling of water in thermosiphon reboilers is beneficial under laminar flow conditions, which corresponds to the results in forced convection as presented by Droegemueller [11]. Here, heat transfer enhancement of 30% without a change in self-circulation was achieved for operating pressures $\leq 200$ mbar and temperature differences $\Delta T \leq 10$ K. For values above these conditions, tube inserts showed no benefits as the boiling of water in plain tubes provided good feedback already.

The circulation ratios for all water experiments were calculated with Eq. (12) and are shown in Fig. 6 with varying static liquid heads, operating pressures, and tube types. They ranged from 73 kg$_{circ}$/kg$_{dist}$ to 540 kg$_{circ}$/kg$_{dist}$, which is a much broader spread than is common for thermosiphon reboilers as noted in other work [12]. Possible reasons for this include the submerged conditions and vacuum operation. These both lead to a shorter evaporation zone, which in turn causes reduced flow resistances for the rising fluid. A closed loop can conduct natural circulation by thermal expansion or a small vapor fraction. Under these conditions, the circulation flow can be much larger than the vapor flow. Heggs and Alane [20] reported a circulation ratio of 100 kg$_{circ}$/kg$_{feed}$ at a system pressure of 200 mbar and a heat flux of 12 kW m$^{-2}$ for the boiling of water in a thermosiphon reboiler. Their maximum circulation ratio in the measurement range was 245 kg$_{circ}$/kg$_{feed}$.$^{-1}$. It should be noted that deviations due to flash evaporation in the exit line and subcooling in the vapor-liquid separator could occur. Especially at small circulation rates, the vapor might not separate efficiently due to the low gas load. In such cases, part of the vapor condensed directly in the vapor-liquid separator and the circulation ratio was artificially increased.

As depicted in Fig. 6, the circulation ratio generally dropped with increasing temperature differences reflecting the effect of two-phase friction on the circulation flow. Heggs and Alane [20] previously demonstrated similar tendencies, as the circulation ratio decays exponentially with an increasing heat flux. However, different to their results, pressure variations had no influence that was identified in this study. A comprehensive view at all data points revealed two tendencies, as denoted by two trend lines in Fig. 6. They almost converged at a temperature difference of 12 K. The upper curve exclusively gathered data points of measurements without inserts under laminar flow condition. Measurements under turbulent flow conditions showed a significantly better performance; those data points were located on the lower curve. In addition, all data points with tube inserts, regardless of whether under laminar or turbulent flow conditions, gathered on the lower curve. Small circulation ratios and therefore relatively high vapor contents were achieved, although inserts did not always prove beneficial to inlet velocity and heat flux, cf. Fig. 5. As previously stated, the use of hiTRAN$^\circledR$-inserts intensified heat transfer at the cost of a greater pressure drop, which could inhibit self-circulation. Because of the close coupling of fluid dynamic and thermal performance, the enhancement of heat transfer achieved by turbulence promotion may be reduced or even eliminated by the reduction in circulation flow. The decreasing difference between the two curves indicates that for water the circulation ratio of plain tubes equals that of tubes with inserts at temperature differences above 12 K. The circulation rate was larger in plain tubes with an increasing heat flux. However, different to their results, Heggs and Alane [20] reported a circulation ratio of 100 kg$_{circ}$/kg$_{feed}$.$^{-1}$ at a system pressure of 200 mbar and a heat flux of 12 kW m$^{-2}$ for the boiling of water in a thermosiphon reboiler. Their maximum circulation ratio in the measurement range was 245 kg$_{circ}$/kg$_{feed}$.$^{-1}$. It should be noted that deviations due to flash evaporation in the exit line and subcooling in the vapor-liquid separator could occur. Especially at small circulation rates, the vapor might not separate efficiently due to the low gas load. In such cases, part of the vapor condensed directly in the vapor-liquid separator and the circulation ratio was artificially increased.

Furthermore, the correlations observed in the circulation ratio can contribute to the design of thermosiphon reboilers. For tubes with inserts, the circulation flow can be calculated for a given or desired product quantity and a driving temperature difference. And for plain tubes, the

![Figure 6. Circulation ratio vs. driving temperature difference $\Delta T$ for water at operating pressures for 100 mbar to 400 mbar and static liquid heads of 110 % and 120 % in plain tubes (open symbols) and inserted tubes (filled symbols).](image-url)
inlet temperature and tube diameter should be defined or estimated additionally to identify the flow regime and the corresponding trend line.

3.2 Evaporation of a Water/Glycerol Mixture in a Thermosiphon Reboiler

In general, evaporation of a water/glycerol mixture is more challenging than that of water not least due to high viscosities and large boiling-point elevation. Fig. 7 depicts inlet velocity, approx. Reynolds number and heat flux depending on temperature differences for operating pressures of 200 mbar and 300 mbar for both tubes at a static liquid head of 110 %. In all cases, initial natural circulation was seen at a temperature difference of 8 K. In contrast to the investigation of water in plain tubes, significantly lower inlet velocities and heat fluxes were measured at the same operating conditions. Therefore, despite the higher viscosities of the water/glycerol mixture, a stable natural circulation may be maintained down to lower circulation rates and inlet velocities. Unlike with water, however, the use of inserts resulted in significant advantages. For all experiments, only laminar flow was present due to the physical properties of the water/glycerol mixture, thus offering greater potential for the use of inserts.

![Image](c.png)

**Figure 7.** Inlet velocity $u_{in}$, Reynolds number $Re$ and heat flux $q$ vs. driving temperature difference $\Delta T$ for a water/glycerol mixture at operating pressures of 200 mbar and 300 mbar and a static liquid head of 110 % with plain tubes (open circles) and with inserts (filled squares). The error bars of inlet velocity show the propagation of uncertainty.

When using inserts at both system pressures, the inlet velocity increased significantly when reaching a threshold value, as also seen in the analogous water experiments. Below this threshold, the inlet velocity and heat flux remained at a low level with enhancements up to 100 %. As temperature difference rose above the threshold, a sudden increase in both parameters was recorded. This threshold ranged from temperature differences of 10 K to 13 K at $p = 200$ mbar and from 11.5 K to 13.5 K at $p = 300$ mbar. Within the threshold range, two operation behaviors existed at the same driving temperature difference supposedly due to Ledinegg instability [19]. The investigation of this instability will be the focus of future work.

At temperature differences of $\Delta T \geq 13$ K, the flow was stabilized at the higher level. Improvements up to five times for inlet velocity and six times for heat flux were achieved by using inserts. However, the inlet velocity seems to reach its maximum of 0.15 m s$^{-1}$ at $p_{sys} = 200$ mbar. This is consistent with the results by Arneth and Stichlmair [1] with an experimentally determined maximum velocity at about 20 K and a simulated maximum at about 15 K. Within the measurement range with plain tubes, no discernible leap of parameters was seen at $p = 300$ mbar. However, at $p = 200$ mbar, the inlet velocity began to fluctuate at $\Delta T = 17$ K, for which the threshold was reached at $\Delta T = 18.5$ K, with a corresponding inlet velocity of 0.12 m s$^{-1}$ and a heat flux of 10 kW m$^{-2}$. Hammerschmidt [2] obtained similar inlet velocities and heat fluxes in a single tube thermosiphon reboiler at $p_{sys} = 200$ mbar.

In summary, the use of inserts shifted the threshold to lower temperature differences and proved highly beneficial for the water/glycerol mixture, when the thermosiphon reboiler is operated in the lower operating range.

Circulation ratios between 56 kg$\text{circ}$.kg$\text{dist}$$^{-1}$ and 500 kg$\text{circ}$.kg$\text{dist}$$^{-1}$ were achieved for the water/glycerol mixture at varied temperature differences, operating pressures and static liquid heads as shown in Fig. 8. Consistent with the experiments with water, the circulation ratio dropped with an increasing temperature difference in two tendencies as presented with two trend lines. The data points derived from plain tubes (open symbols) gathered around on the upper curve, while the data points from inserted tubes (filled symbols) gathered on the lower curve. Interestingly, operating points at the lower and higher level as shown in

![Image](d.png)

**Figure 8.** Circulation ratio vs. driving temperature difference $\Delta T$ for a water/glycerol mixture at operating pressures between 100 mbar and 300 mbar and static liquid heads of 110 % and 120 % in plain tubes (open symbols) and inserted tubes (filled symbols).
Fig. 7 showed the same circulation ratio. The use of hiTRAN®-inserts proved superior to plain cylindrical tubes for the evaporation of the water/glycerol mixture. Unlike the pinching of the fit curves for the water experiments at \( \Delta T = 12 \) K, a further advantageous operating range at temperature differences above 19 K can be expected. This was corroborated by Fig. 7, since the higher level of inlet velocity and heat flux was barely reached or not at all in experiments without inserts.

4 Conclusions

In this study, the boiling of water and a water/glycerol mixture in a thermosiphon reboiler with both plain tubes and tubes equipped with hiTRAN®-wire matrix inserts was investigated experimentally at low operating pressures of 100 mbar (abs) \( \leq p \leq 400 \) mbar (abs) and under flooded condition (static liquid head \( h_{s,*} \geq 110 \% \)). For the boiling of water, the use of inserts was only advantageous at operating pressures below 200 mbar under laminar flow conditions. Here, experimental results determined a heat transfer enhancement of 30 % and no change in inlet velocity. Above 300 mbar, turbulent flow prevailed. For this flow regime, the use of inserts showed no benefit. Nevertheless, the circulation ratios of boiling in plain tubes with turbulent flow and in tubes with inserts were similar, indicating that the enhancement of heat transfer due to the turbulence promotion was compensated by the reduced circulation flow caused by the increased pressure drop.

The boiling of a water/glycerol mixture was investigated under variation of driving temperature differences between 7 K and 19 K under flooded condition. By using hiTRAN®-inserts, a threshold range was identified, in which two operating points exist under identical operating conditions supposedly due to Ledinegg instability. Below the threshold, improvements up to 100 % were obtained, while above this threshold, significant improvements were achieved with a five times larger circulation flow and a six times larger heat transfer. By using wire matrix inserts at \( p_{sys} = 200 \) mbar (abs), a reboiler tube inlet velocity of \( 0.12 \) m s\(^{-1}\) and an integral heat flux of 10 kW m\(^{-2}\) were achieved at a driving temperature difference of 13 K, while 19 K is required for plain tubes. Further investigations will address the operation of thermosiphon reboilers under not flooded condition \( (h_{s,*} \leq 100 \%) \) and the analysis of the observed instability.

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### Symbols used

- \( A \) [m\(^2\)] Surface
- \( C \) [-] Circulation ratio
- \( c_p \) [J kg\(^{-1}\)K\(^{-1}\)] Specific heat capacity
- \( d \) [m] Diameter
- \( h \) [m] Distance
- \( \Delta h_v \) [J kg\(^{-1}\)] Enthalpy of evaporation
- \( h_{s,*} \) [%] Static liquid head, submergence
- \( L \) [m] Length
- \( m \) [kg s\(^{-1}\)] Mass flow
- \( n \) [-] Number of tubes
- \( p \) [Pa] Pressure
- \( Q \) [W] Heat flow
- \( \dot{q} \) [W m\(^{-2}\)] Heat flux
- \( Re \) [-] Reynolds number
- \( s \) [m] Wall thickness
- \( T \) [°C] Temperature
- \( T_s \) [°C] Saturation temperature
- \( u \) [m s\(^{-1}\)] Velocity
- \( x \) [mol mol\(^{-1}\)] Mole fraction

### Greek Symbols

- \( \eta \) [kg m\(^{-1}\)s\(^{-1}\)] Viscosity
- \( \rho \) [kg m\(^{-3}\)] Density

### Subscripts

- \( circ \) Circulation
- \( CL \) Circulation line
- \( cs \) Cross section
- \( dist \) Distillate
- \( g \) Gas
- \( Gly \) Glycerol
- \( hl \) Heat loss
- \( ht \) Heat transfer
- \( in \) Inlet
- \( l \) Liquid
- \( o \) Outer
- RT Reboiler tube
- \( sys \) System

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