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ENHANCED VACUUM CONDENSATION IN VERTICAL TUBES IN THE PRESENCE OF NONCONDENSABLE GAS

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ABSTRACT

Enhancement and optimisation of heat and mass transfer process are the mainstay to an environment- and climate-friendly production process. It is particularly important to operate equipment and systems as energy-efficient as possible. With a better understanding of the intensification opportunities typical drawbacks in the heat exchanger design can be prevented. Retrofitting with turbulence promoters may allow for debottlenecking, thus avoiding the need to purchase new equipment. In this work it is investigated in a shell and tube heat exchanger at vacuum condensation conditions how a non-condensable gas fraction in the vapour phase effects the condenser performance. Condensation is often realized on the shell side with the cooling water on the tube side as the formed condensate film acts as an additional heat transfer resistance as well as non-condensable components in the vapour phase. However, for corrosive- or fouling-prone fluids condensation within vertical tubes has proven as beneficial alternative. Solutions to inhibit the disadvantages of vertical vacuum condensation are necessary. Therefore, hiTRAN® inserts were used to enhance the condensation process and observe the influence of turbulence promoters in condensation services.

1. INTRODUCTION

Condensation on a vertical surface can be limited by the gas phase as well as by the liquid phase. Processes in which a narrow-boiling mixture or a pure substance is condensed are mainly limited by the thermal resistance of the formed film [1]. If possible, the condensate film may be removed from the wall, which would allow similar conditions to a dropwise condensation, characterised by extremely high heat transfer. If a wide-boiling mixture is condensed in the process, least convenient a condensing component and an inert component, the heat transfer is limited by the vapour phase. Along the condensation path, the composition of the vapour changes severely and leads to a decrease of the vapour phase dew point. In order to maintain condensation, the vapour must be cooled. In addition, a second distributing gradient occurs in radial direction to the cold wall and leads to an enrichment of the low-boiling respectively the inert component between condensate film and bulk vapour phase. The decreasing partial pressure of the condensing component in the boundary layer leads to a local reduction of the dew point in the vicinity of the condensate film. The boundary layer impedes the heat transfer between vapours and the condensate on the tube wall. It acts as an additional thermal resistance, especially towards the end of the condensation process. [1] In these cases, process intensification through mixing is particularly useful in order to eliminate the formed boundary layers and to enhance the necessary heat transfer. Using enhancement methods for turbulence intensification already showed a positive impact on other processes such as single-phase flow [2] or two-phase flow systems [3].

2. EXPERIMENTAL SETUP

To investigate the condensation behaviour of a binary mixture with a non-condensable component in vertical tubes, a test rig was used involving a pillow-plate heat exchanger (W200) as a thermosiphon reboiler and a shell-and-tube heat exchanger (W300) as a condenser supplemented with a plate heat exchanger (W301) as post-condenser. 1-Hexanol is used as the product to be evaporated and condensed with nitrogen added as non-condensable component. With 300 mbar system pressure, the gas mixture enters the condenser at the head. Here it is fed through the 5 tubes with OD x s x L = 20 x 2 x 1800 mm, while water with T_{in} = 80 °C is used as a coolant counter-current on the shell side.

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For integral condensation, a thermodynamic equilibrium with identical temperatures of vapour and condensate phase is assumed. Especially in the case of poor mixing at low vapour velocities, this is not necessarily given and can lead to uncertainties in the calculation. As will be shown later, turbulence promoters may significantly improve mixing. hiTRAN® wire matrix inserts are implemented in all five heat exchanger tubes and compared to unequipped tubes (Figure 1, left).

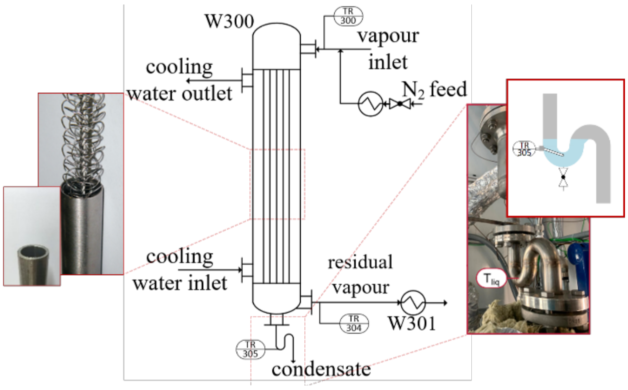

Figure 1: Schematic setup of the shell and tube heat exchanger with inner tube variation from empty to inserts (left) and the siphon system for a sufficient liquid outlet temperature measurement (right).

Exit temperature of the condensate film was measured via a siphon solution (Figure 1, right). With a hold-up of 150 ml, multiple replacement of the holdup can be expected.

3. RESULTS

Empty tube experiments with an increasing nitrogen fraction at the inlet show a significant decrease in condenser performance (Figure 2, left). The diminished heat transfer leads to a greater ratio of partial condensation thus the residual vapour fraction of hexanol at the outlet is increasing too.

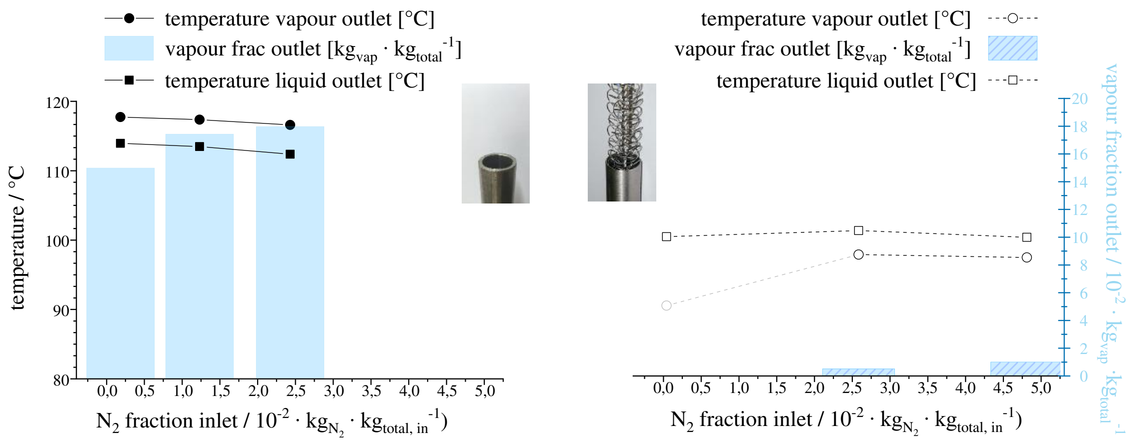

Figure 2: Condensation behaviour of hexanol at different nitrogen inlet fractions in empty tubes (left) and inserts (right): dots: vapour phase inlet temperature; squares: vapour phase outlet temperature; bars: vapour fraction of hexanol at outlet.

As the non-condensable accumulates along the axial path, the nitrogen fraction at the outlet is significantly higher compared to the inlet. As a result, the saturation temperature of the condensing component decreases and the product and cooling side temperature driving force is reduced. Further, accumulating nitrogen results in an additional thermal resistance which causes a rising temperature gap between condensate and vapour bulk phase. The integration of hiTRAN® elements has a drainage and mixing impact on the condensation process. For one thing, the drainage of the forming liquid film decreases the thermal resistance of the film, for another, the mixing of the two-phase flow decreases the concentration gradient in the vapour phase thus intensifies the heat transfer and in case of a vapour outlet flow narrows the temperature gap.

Experimental results reveal the poor condensation performance of the bare tubes based on the heat flow distribution in the two condensers. The shift of partial condensation runs in accordance with the heat flow allocated to the main condenser (W300) and the post-condenser (W301).

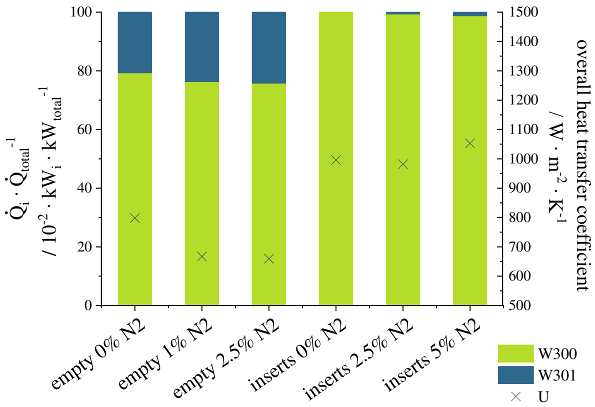

Figure 3: Heat fraction (bars) at different nitrogen fractions at the condenser inlet in empty tubes (left) and with inserts (right) and the corresponding overall heat transfer coefficient for W300 (points).

For the case of a nitrogen fraction of 2.5% at the condenser inlet the transferred heat flow in the main condenser can be lifted from 75% to 99.3%. Considering the overall heat transfer coefficient of the heat exchanger the value enhances by almost 50%.

However, mixing the two-phase flow in the tube through the inserts suffers from an increasing pressure drop. In this setup the pressure loss with inserts was more than 20 times higher than in regular empty tubes mainly caused by the existing hexanol vapour flow as the nitrogen volume fraction is insignificant small. The condensation is strongly influenced by the local process pressure as pressure loss is lowering the condensation temperature of the vapour. To achieve a better overall efficiency by using enhancements in tubes, one must balance an intensified film and bulk side turbulence with a minimum pressure drop penalty. In order to reduce the pressure loss influence to a minimum, solutions with partially equipped pipes may be considered.

4. CONCLUSION

Overall experiments show that the presence of a non-condensable component has an impact on the condensation process and leads to a poor condenser performance. This can result in the heat exchanger no longer being able to fulfil the necessary operating conditions. Residual vapour leaves the condenser. These issues can be addressed with tube side installed enhancements. The condenser performance can be increased by 50%, however the pressure drop rises concurrently.

ACKNOWLEDGEMENTS

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