Measurement of supercritical heat transfer to R125 in horizontal flow

J Van Nieuwenhuyse[1], A De Meulemeester[1], M De Paepe[1,2] and S Lecompte[1,2]

[1] Department of Electromechanical, Systems and Metal Engineering, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium
[2] FlandersMake@UGent - Core lab EEDT-MP, flandersmake.be

E-mail: jera.vannieuwenhuyse@ugent.be

Abstract. Supercritical heat transfer has already been studied extensively, however, the majority of these studies focused on water or CO_2. Data on refrigerants, which are used in for example transcritical or supercritical organic Rankine cycles or heat pumps, is scarce. Nonetheless, this data is crucial in order to size the heat exchangers used in these systems without significant overdimensioning. Therefore it is necessary to gain insight into the complex nature of supercritical heat transfer. For that purpose, experimental data on supercritical heat transfer to the refrigerant R125 is discussed in this work. Measurements were performed on a previously built test rig, where the refrigerant flowed in a horizontal tube with an inner diameter of 24.77 mm. Pressure, mass flux and heat flux were varied, and their influence on supercritical heat transfer was investigated. In general, heat transfer is enhanced for an increase in mass flux or decrease in heat flux, and no distinct effect of pressure on the heat transfer is measured.

1. Introduction

Heat exchangers are essential components in many thermodynamic cycles, such as power and heat pump cycles. In order to size these heat exchangers without large safety factors and the risk of oversizing, accurate data and knowledge is required about the heat transfer. In applications such as transcritical or supercritical organic Rankine cycles, CO_2 cycles or heat pumps, the working fluid is first pressurized above its critical pressure (p_c) before it enters the heat exchanger [1]. Supercritical heat transfer takes place there, which cannot be accurately predicted by constant property correlations such as the Gnielinski or Dittus-Boelter correlation. This is due to the fact that the working fluid experiences large property variations when it passes its pseudo-critical temperature (which is the temperature, corresponding to a supercritical pressure, where the specific heat capacity of the working fluid is at a maximum). When the supercritical pressure is raised, the pseudo-critical temperature increases and the variations are less strong. These variations in thermo-physical properties will heavily influence the heat transfer, as during heat addition the fluid transitions from a liquid-like to vapour-like fluid (or vice versa in case of heat rejection).

Supercritical heat transfer has already been studied, but the main focus of the studies has been on water or CO_2 and the majority of the investigated geometries have been vertical tubes [2, 3]. Research and experimental data on refrigerants flowing horizontally is scarce. In the case of heat transfer to refrigerants in horizontal flow, R134a has been the most investigated working fluid. Measurements have been performed for several tube diameters and geometries (both smooth and ribbed tubes) [4, 5, 6, 7, 8, 9]. Other researched refrigerants are R1234yf [10], NOVEC 649 [11] and R125 [12]. The effect of pressure, buoyancy, mass flux and heat flux on the local heat transfer were measured, and in some studies new correlations or criteria were developed. It was overall found that heat transfer improved for an increase in mass flux and a decrease in heat flux. The effect of pressure was more complicated, as it depended on other parameters, but in general, a pressure increase resulted in a drop in heat transfer.

To extend the knowledge about supercritical heat transfer, an experimental campaign was performed of which results are discussed in this work. Experiments were performed on the refrigerant R125 flowing in a horizontal tube with an inner diameter of 24.77 mm. R125 has a relatively low critical temperature and pressure of 66.02°C and 36.18 bar, respectively, which makes it a suitable working fluid for supercritical applications.

2. Experimental campaign

The experiments were performed on a test rig which has been previously built by Lazova et al. [12]. In this test rig, R125 is preconditioned to the required temperature and pressure by sufficient preheating and a volumetric pump, respectively. In the test section, which is constructed as a horizontal countercurrent tube-in-tube heat exchanger with a length of 4 m, R125 flows in the inner tube (with an inner diameter of 24.77 mm) and heat is added to it by a heating fluid (a thermal oil) which flows in the annulus. Several Pt100s, thermocouples and other measurement equipment were also installed on the test rig in order to perform the data reduction, discussed next.

In the performed experiments, parameters such as mass flow rate, heat flux and pressure were altered in order to see the effect on the local heat transfer coefficients. The heat transfer coefficients of the refrigerant (htc_r) were calculated according to:

$$htc_r = \frac{\dot{q_r}}{T_{wi} - T_{b,r}} \tag{1}$$

where $\dot{q_r}$ is the heat flux to the refrigerant, T_{wi} the inner wall temperature of the inner tube and $T_{b,r}$ the measured bulk temperature of refrigerant. T_{wi} in its turn was calculated based on the measured temperature of the oil, according to:

$$T_{wi} = T_{b,hf} - \dot{Q} \cdot [\frac{1}{htc_{hf} \cdot \pi \cdot d_o \cdot L} + \frac{ln(\frac{d_o}{d_i})}{2 \cdot \pi \cdot k \cdot L}] \tag{2}$$

where $T_{b,hf}$ is the measured bulk temperature of the oil, $\dot{Q}$ is the heat transfer rate, htc_{hf} is the heat transfer coefficient of the oil, which is based on the Dirker and Meyer correlation [13], d_o and d_i are the outer and inner diameter of the inner tube, L is the length of the section and k is the thermal conductivity of the tube.

Uncertainties on the measurement equipment were ± 0.1K for both the Pt100 and thermocouple measurements, ± 6kPa on the pressure measurements and ± 1% on the mass flow measurements. Uncertainties on the fluid properties of oil were ± 1 J/kgK, ± 0.0001 W/mK and ±0.001 mPa·s for the specific heat capacity, thermal conductivity and dynamic viscosity, respectively. The uncertainty on the thermal conductivity of R125 was equal to ± 3%. An error of 3% was taken for the Dirker and Meyer correlation [13].

3. Results and Discussion

In the graphs below, the local heat transfer coefficients are plotted in function of the refrigerant bulk enthalpies. The dotted lines represent the pseudo-critical bulk enthalpies corresponding to the supercritical pressure of that data set. In the accompanying legend, the pressure (relative to the critical pressure p_c), the refrigerant mass flux G_r and the heat flux q_r of each data set are depicted. In Figure 1 the influence of pressure on the heat transfer is presented for high mass flux and low heat flux, showing that pressure has no distinct effect under the current measurement conditions. In general, the same holds for other measurement conditions as well. A possible explanation is that due to the large diameter of the test section, buoyancy is dominating the heat transfer under every measurement condition, resulting in a limited pressure effect [4, 10].

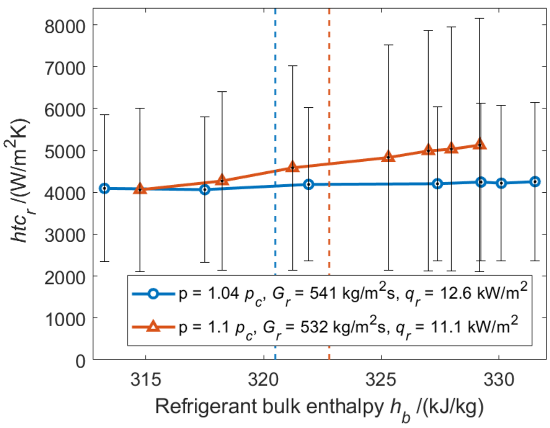

Figure 1. Pressure influence on local heat transfer coefficient.

Figure 2 and Figure 3 show the effect of changing the mass flux or heat flux on the heat transfer, respectively. To increase readability, the uncertainty intervals in Figure 3 have been omitted. In line with what is overall found in literature, a rise in mass flux results in a rise in heat transfer. Also similar to previous literature, heat transfer, in general, decreases for an increase in heat flux.

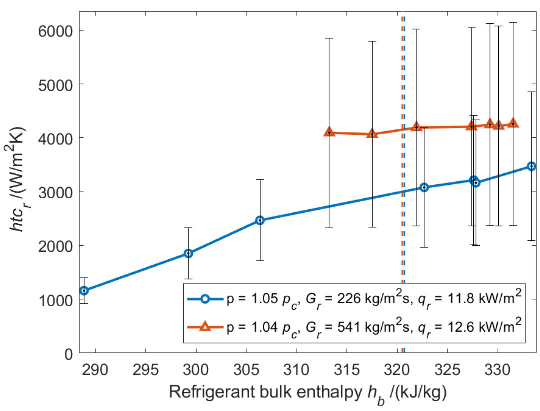

Figure 2. Mass flux influence on local heat transfer coefficient.

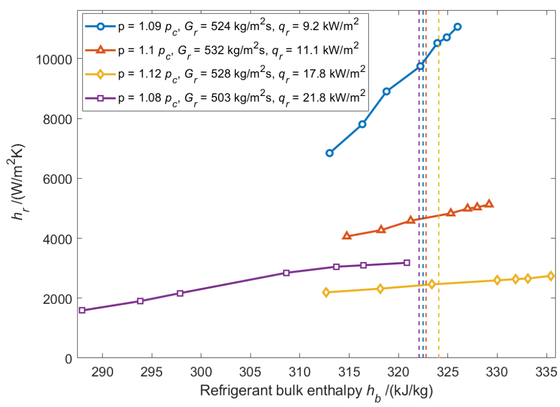

Figure 3. Heat flux influence on local heat transfer coefficient.

To further extend the database of tested refrigerants, the current test rig will be altered in future work. In addition, wall temperature measurements will also be added in order to visualize the influence of buoyancy on heat transfer and to improve the accuracy of the results.

4. Conclusion

Knowledge about supercritical heat transfer to refrigerants needs to be extended, therefore, in this work, experimental data on supercritical heat transfer to the refrigerant R125 flowing horizontally is presented and discussed. Similar to previous literature, in general, heat transfer is enhanced by increasing the mass flow rate of refrigerant or reducing the heat flux. The pressure does not have a clear effect, which could indicate that due to the large diameter buoyancy is dominant in the measurements.

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