UK Heat Transfer Conference 2021
UKHTC2021

17th UK Heat Transfer Conference (UKHTC2021)
4-6 April 2022, Manchester, UK

STUDY OF R-1233ZD(E) CONVECTIVE BOILING HEAT TRANSFER AT MODERATE REDUCED TEMPERATURE

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ABSTRACT

Miniaturization is currently one of the most investigated topics in heat transfer but it requires capability of removal of high heat fluxes, usually accomplished by the phase change. Flow boiling is characterized by one of the highest values of heat transfer coefficients. However, despite many in-depth studies made, flow boiling phenomena in mini- and microchannels is still not fully understood. Specifically, there is a gap in knowledge on flow boiling of low boiling point fluids at moderate and high saturation temperatures and moderate/high values of reduced pressure. The paper presents results of experimental research of R1233zd(E) at saturation temperature of 115 °C. Experiment has been carried out for tube with 2 mm inside diameter. The heat flux ranged from 20 to 45 kW/m^2, mass velocity ranged from 200 to 1000 kg/m^{2}s, and the whole range of vapor quality was covered. The effects of mass velocity and heat flux and flow structure were analysed. The heat transfer coefficient for bubbly/slug flow decreases with vapor quality and is independent from mass velocity and heat flux. In annular flow the heat transfer coefficient is independent from heat flux and increases with mass flux. The relationship with vapor quality depends on mass velocity – for lower values it decreases or is independent and for higher increases with vapor quality. The pre-dryout data was compared with in-house model with mean absolute error of 22.01%.

1. HEAT TRANSFER COEFFICIENT AT HIGHER VALUES OF SATURATION TEMPERATURE

Increase of parameters of liquid–vapor phase-change phenomena has significant impact on heat transfer. At high saturation temperatures high vapor density, low surface tension, high vapor viscosity and low liquid viscosity can be observed. Heat transfer mechanisms are strongly dependent on the flow parameters (mass velocity, heat flux and vapor quality), the working fluid, the geometry and the saturation conditions. Unfortunately data available in literature for this region is very sparse. Charnay et al. [1] found at high saturation temperatures the impact of nucleate boiling is more significant than in conventional conditions. Usually an increase of reduced pressure leads to an increase of heat transfer, but in some cases the process is opposite. Del Col [2] studied flow boiling of R134a, R22, R125 and R410A at high reduced pressures covered in a range between 0.2 and 0.5. He confirmed that nucleate boiling plays a key role at high evaporating pressure. Experiments have been well correlated using own modification of Gungor-Winterton correlation [3]. Padovan et al. [4] reported data for flow boiling of R134a and R410A inside a horizontal microfin tube at saturation temperatures of 30°C and 40°C. The influence of saturation temperature was found only in low vapor quality region, due to the effect of the nucleate boiling. Charnay et al. [1, 5, 6, 7] studied boiling of R245fa in a 3mm inner diameter circular tube at saturation temperatures ranging from 60°C to 120°C. The analysis of the results led to highlight the key role of nucleate boiling at high saturation temperature. Belyaev et al. [8] presented results of an investigation of flow boiling heat transfer of R113 and RC318 in two vertical channels with diameters of 1.36 and 0.95 mm and lengths of 200 and 100 mm, respectively, under different combinations of reduced pressure, liquid subcooling, mass flux and heat load. Inlet fluid temperature varied from 30°C to 180°C. For high reduced pressure ($p_r > 0.4$) qualitative differences in flow boiling and convection heat transfer characteristics in minichannel do not differ from the results obtained in conventional tubes. Jakubowska at al. [9] conducted experimental study of flow boiling heat transfer of HFE7000 in a vertical tube of 2.3 mm inner diameter for the saturation temperatures from 30 to 54 °C. Experiments

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identified the effects of heat flux, mass flux and saturation temperature and their influence on the flow boiling heat transfer coefficients. The flow boiling heat transfer coefficient increased with increasing mass flux. However, the effect of increasing mass flux was less obvious and almost negligible on heat transfer coefficients. As the saturation temperature increases the flow boiling heat transfer coefficient also increases. The flow boiling heat transfer coefficient increases significantly with the increasing heat flux, which leads to the conclusion, that nucleate boiling is dominant. The heat transfer coefficient, initially, slightly decreases with vapor quality in the low-quality region and then increases with the further increase in vapor quality. After the heat transfer coefficient reaches the maximum value, it decreases as the vapor quality goes up to a high vapor quality region. Correlation by Mikielewicz et al. [10, 11] predicted experimental results with the lowest mean error, i.e. AMD=13.12% with over 92% of data being within 30% error band.

2. DATA PROCESSING AND REDUCTION

Heat transfer coefficient and pressure drop are measured during experiment. Experiment is carried out by monitoring mass flux and calculated values of vapor quality and saturation temperature. Data is recorded when certain conditions are satisfied in a time of 10 minutes: the deviation of mass flux lower than 1.5 % of current value, the deviation of saturation temperature not higher than 0.5 °C and vapor quality deviation not higher than 1 %.

Vapor quality at position y of the test section is calculated with the local enthalpy calculations:

$$x_y = \frac{h_1 + \frac{\dot{Q}_{test}}{\dot{m}}\frac{l_y}{l_{test}} - h_{1,saturated}}{h_{lv}} \tag{1}$$

Where: x_y is vapor quality at the inlet of test section, h_1 is enthalpy at the inlet of preheater calculated on the basis of temperature and pressure measurements, Q_{test} is power output delivered to test section, l_y is position of the measured point and l_{test} is the length of test section, $h_{1saturated}$ is enthalpy for vapor quality equal 0.0 for saturation temperature at the inlet of test section and h_{lv} is latent heat of vaporization calculated for saturation temperature at the inlet of test section.

Saturation temperature at position y is calculated from expression 2 with the use of EES software:

$$T_{sat.y} = T_{sat}(P_{sat.y}) \tag{2}$$

where saturation pressure is calculated with following equation:

$$P_{sat.y} = P_{sat.test2} - (\Delta P_{total}) \cdot \left(\frac{l_y}{l_{test}}\right) \tag{3}$$

Temperature at the inner wall at position y (first thermocouple) is deduced from equation number 4 which was derived based on the assumption of uniform heat generation in the channel.

$$T_{wall.in.y1} = T_{wall.out.y1} + \frac{\dot{q}_V\left(r_{outer}^2 - r_{inner}^2\right)}{4 \cdot \lambda_{SS}} - \frac{\dot{q}_V \cdot r_{outer}^2}{2 \cdot \lambda_{SS}} \cdot \ln\left(\frac{r_{outer}}{r_{inner}}\right) \tag{4}$$

where $T_{wall.out.y1}$ is temperature measured at position y, q_v is volumetric heat generation, r_{outer} is radius of outer wall, r_{inner} is radius of inside wall and λ_{SS} is heat conductivity of a tube wall. Temperature inside the tube wall is calculated as average from both thermocouples located at position y:

$$T_{wall.in.y} = \frac{T_{wall.in.y1} + T_{wall.in.y2}}{2} \tag{5}$$

Finally the heat transfer coefficient at position y is calculated with a use of equation number 6:

$$\alpha_y = \frac{\dot{q}_{test}}{T_{wall.in.y} - T_{sat.y}} \tag{6}$$

Where q_{test} is heat flux generated in a tube by Joule effect.

3. EXPERIMENTAL SETUP

The present study investigates the heat transfer of R-1233zd(E) during flow boiling inside a 2 mm diameter, 300 mm long stainless steel tube. Experiment is accomplished for saturation temperature of 115˚C and reduced pressure of 0.4. Heat flux in the experiment is between 15 and 45 kW/m^2 whereas mass velocities in the range 200 - 1000 kg/m^{2}s, respectively. Mass flow rate is measured by the Coriolis-type flowmeter with 0.3% accuracy of full scale. Table 1 presents the experimental details.

Table 1: Range of the experimental parameters in the study

Parameters	Values	Uncertainty
d (mm)	2.0	±0.1
l (mm)	300	±0.2
G (kg/m^{2}s)	400 - 1000	±6.5%
$\dot{q}_{preheater}$ (kW/m^2)	0.1 – 50.0	±3.5 %
$\dot{q}_{test\ section}$ (kW/m^2)	15.0 – 45.0	±3.5 %
T_{sat} (˚C)	115	±1.5
P_{sat} (kPa)	1430	±5.6

Experimental facility is schematically presented in figure 1. Figure 2 presents a photograph of actual experimental facility. It consists of the refrigerant and oil loops. R-1233zd(E) is pumped by the diaphragm pump, it next passes through the Coriolis-type flowmeter, microvalve, preheater, test section and then it can goes directly to condenser either through the by-pass or the visualisation section.

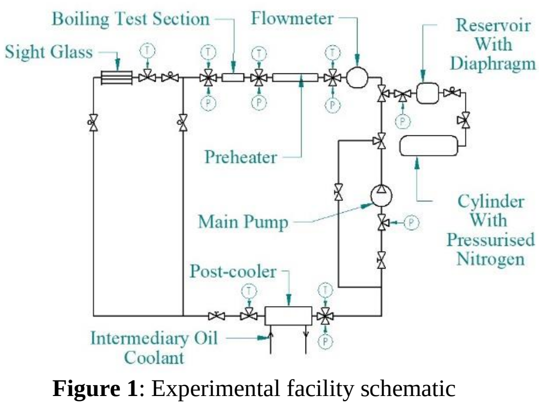

Figure 1: Experimental facility schematic

Figure 2: Experimental facility

The mass flow is controlled either by rotational velocity of the pump, or by the by-pass valve. The saturation pressure in the system is sustained with the aid of the bladder accumulator which is filled with nitrogen on one side and the liquid refrigerant on the other side of the bladder. Additionally, accumulator serves as a flow and pressure stabilizer for the pump. A three meters long spirally formed preheater is preparing the required parameters for the test section, usually to have the saturated conditions at inlet or in some cases initially evaporated. Preheater is used to control the vapor quality at the test section inlet. Preheater and test section are heated by the Joule effect by two separate DC voltage suppliers. Test section is 300 mm long tube with inside diameter of 2 mm and outside diameter of 4 mm. Two pressure transducers and two type-K thermocouples are installed at the inlet and outlet of the test section. Eighteen K-type thermocouples are soldered to the wall of test section (respectively nine at the bottom and nine at the top). Preheater and test section are electrically insulated by PEEK separators. Visual test section consist of borosilicate tube with inside diameter of 3 mm and high speed camera. Vapor exiting the test section is condensed and subcooled in the brass plate HX.

4. RESULTS

Presented below are the single phase measurements of pressure drop and heat transfer to test the consistency with the well-established empirical correlations due to Blasius [12] and Nusselt number due to Gnielinski [13]. Results of single-phase test section validation are presented in Figures 3 and 4.

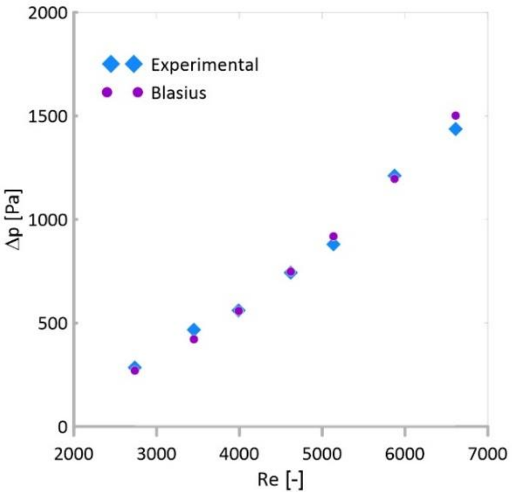

Figure 3: Comparison of the experimental single-phase pressure drop with values obtained due Blasius [12]

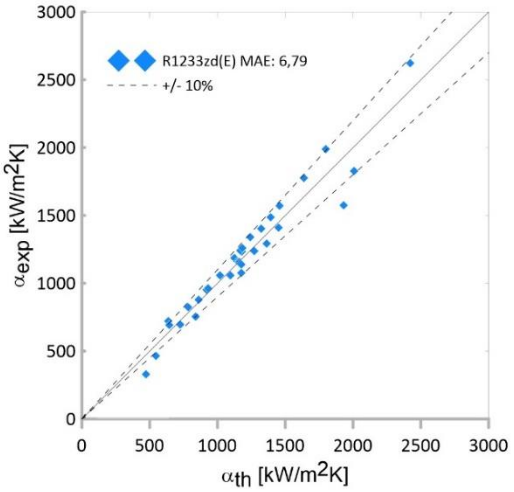

Figure 4: Comparison of the single-phase test results α_{exp} with α_{th} obtained using the Gnielinski correlation [13]

Achieved results of single-phase test section validation provided good agreement with well-known correlations. The experimental heat transfer coefficient was predicted with mean absolute error of 6.79%. Figures 4 and 5 presents influence of mass flow on heat transfer coefficient for two different heat fluxes, namely 20 and 30 kW/m^2.

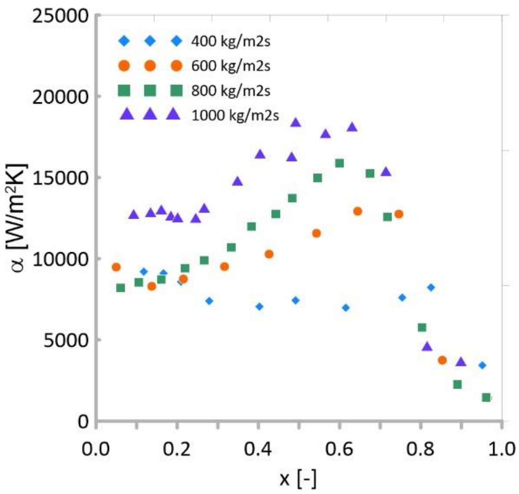

Figure 4: Influence of mass flow on heat transfer at constant heat flux q_w=20 kW/m^2, p_r=0.4

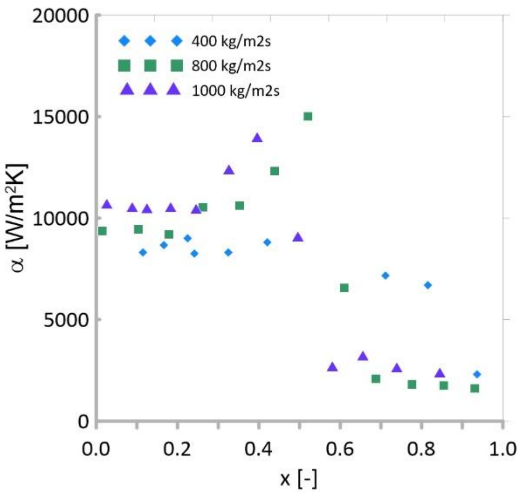

Figure 5: Influence of mass flow on heat transfer at constant heat flux q_w=30 kW/m^2, p_r=0.4

For lower values of mass velocity (400 kg/(m^{2}s)) the heat transfer coefficient is independent from vapor quality. For higher values of mass velocity (600, 800 and 1000) an increase of heat transfer coefficient is observed. It can be concluded that at lower values of mass velocity the bubbly/slug flow structure is present. In annular flow the increasing trend in heat transfer is observed. For higher values of mass flux (600-1000 kg/m^{2}s) the heat transfer coefficient is increasing with vapor quality until the dryout occurs, where a sudden drop in heat transfer is observed.

Figures 6 and 7 presents influence of heat flux on heat transfer coefficient. The collected data show small influence of heat flux on the value of heat transfer coefficient. For smaller values of mass fluxes (400 kg/m^{2}s) the heat transfer coefficient is independent or slightly decreases with increasing of vapor quality whereas for higher values (600-1000 kg/m^{2}s) the increase of heat transfer coefficient is observed followed by the onset of dryout and subsequent deterioration of heat transfer.

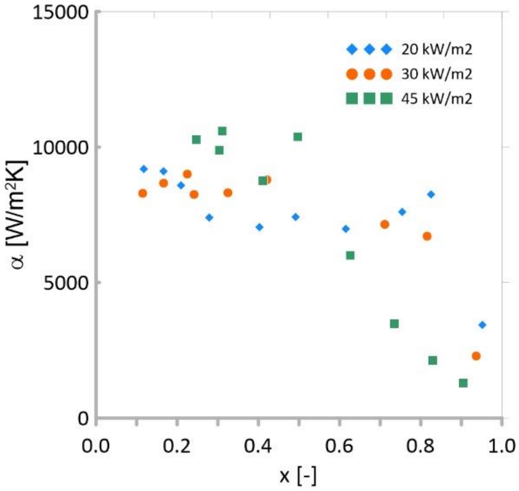

Figure 6: Influence of heat flux on heat transfer coefficient for mass flux equal 400 kg/m^{2}s

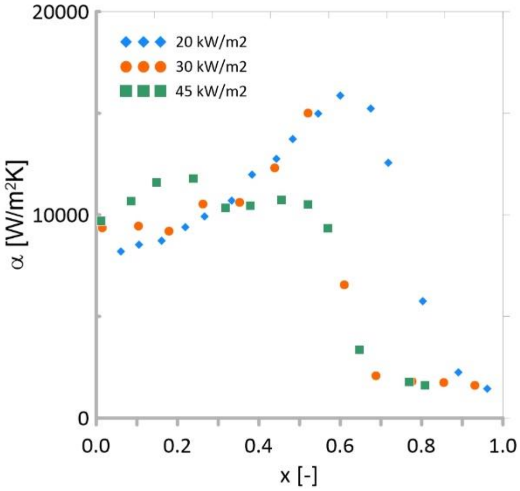

Figure 7: Influence of heat flux on heat transfer coefficient for mass flux equal 800 kg/m^{2}s

Figure 8 presents some of the photos of flow structure captured during experiment. A general observation is that the bubbly flow extends longer than in case of small reduced pressure experiments, where transition to bubbly flow occurs at x=0.1. Figure 9 shows the results of modelling the pre-dryout data with the use of in-house model [10]. Mean absolute error of modelling is equal 26.85% and 57.14% of data fall into 30 % error band. The in-house model will be further scrutinised to include the effects of reduced pressure, present in the collected data.

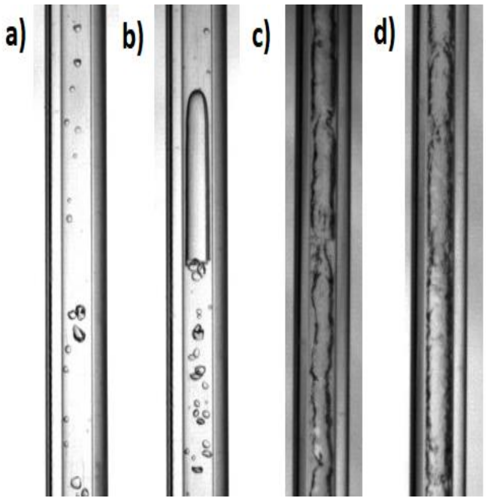

Figure 8: Visualization of two-phase flow during flow boiling (mass flux G = 400 kg/m^{2}s; heat flux q = 30 kW/m^{2}K; vapor quality: a) x = 0.07; b) x = 0.22; c) x = 0.65; d) x = 0.95)

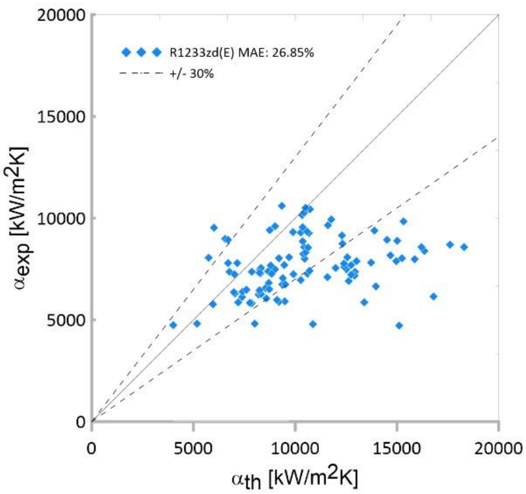

Figure 9: Comparison of the flow boiling test results α_{exp} with α_{th} obtained using the in-house correlation [10]

5. CONCLUSIONS

Impact of heat flux, mass flux, vapor quality and flow structure on heat transfer coefficient was discussed. During bubbly/slug flow the heat transfer coefficient decreases with vapor quality and is rather independent from heat flux. In annular flow the heat transfer coefficient is independent from heat flux and increases with mass flux. The relationship with vapor quality depends on mass velocity – for lower values it decreases or is independent and for higher increases with vapor quality. Comparison of pre-dryout data with data modelled with a use of in-house correlation provided good results with mean absolute error at the level of 26.85% and 57.14% of data falling within 30% error band.

ACKNOWLEDGEMENTS

Work was funded from project 2017/25/B/ST8/00755 by National Science Centre, Poland

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