FLOW BOILING HEAT TRANSFER CHARACTERISTICS OF LOW GLOBAL WARMING POTENTIAL REFRIGERANTS IN A VERTICAL MINI-CHANNEL

by

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Flow boiling heat transfer characteristics in narrow channels have been investigated extensively by researchers due to its wide range of applications in micro-electromechanical systems, however, being a complex transport process the controlling mechanisms still lack clarity in understanding. Refrigerants related environmental hazards also urged to look for alternative environment friendly refrigerants. It has been noticed that relatively less information is available in the literature specifically for environmentally benign mediums. This study is focused on experimental findings for flow boiling heat transfer performance of low global warming potential refrigerants (R152a, R600a, and R1234yf). The test object was a vertical stainless steel tube (1.60 mm inner diameter and heated surface length 245 mm), experiments were done under upward fluid-flow conditions. The tested conditions were: heat flux 5-245 kW/m^2, 50-500 kg/m^{2}s mass velocities while saturation temperatures were 27 °C and 32 °C. The effects of operating parameters like heat and mass fluxes, saturation temperature, and vapor quality on heat transfer were analyzed in detail. It was noticed that heat transfer coefficients were significantly influenced by heat flux and operating pressure level whereas the same were not significantly affected by mass flux and vapor quality. The experimental data of heat transfer was compared with the prediction from various macro and micro scale correlations from the literature.

Key words: *flow boiling, heat flux, mini-channel, R152a, R600a, R1234yf, correlations*

Introduction

Exchange of thermal energy is involved in diverse applications, thermal power plants, nuclear reactors, electronic chips, refrigerators are few application areas. Efficient design of thermal systems for such applications requires better understanding of involved transport mechanisms. Compact channels (with $d \leq 3$ mm) offers many potential benefits over their conventional counterparts. Better thermal performance, less fluid and material requirement, and relatively high pumping power for fluid circulation are key operating characteristics for devices

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made from such compact channels. Phase change heat transfer process (boiling/condensation) has the capability to withstand high heat flux and better control for local hot spots [1].

The R134a had been used in a wide variety of applications within refrigeration and air conditioning industry [2]. While this medium has good thermophysical properties and is also free from chlorine but it does have high global warming potential, GWP =1430 [3]. The industry is now in search of possible sustainable alternatives as legislators across the globe are restricting its utilization within refrigerators and air conditioners [4-6].

The exchange of thermal energy during flow boiling in a circular channel (2.46 mm diameter and a channel length of 0.9 m) for Freon-12 has been reported by Tran *et al.* [7]. The authors compared collected results with their earlier findings with R-113 using a circular tube with ID of 2.92 mm [8]. The data was collected for 3.6-129 kW/m^2 heat flux and 44-832 kg/m^{2}s mass velocities and covered about 94% change of vapor quality in the test section. The experimental data was used for development of a correlation for prediction of boiling heat transfer coefficients (HTC) [7]. The developed correlation predicted their results within ±15% from experimental findings. The purposed new correlation also includes surface tension which was not considered in the correlation of Lazarek and Black [9]. It was noticed that heat transfer performance was significantly controlled by applied heat flux with an insignificant effect of mass flux. Similar trends were also reported by Lazarek and Black [9] for a circular tube with 0.31 cm internal diameter and heated length 12.3 and 24.6 cm.

Experimental findings on flow boiling heat transfer and pressure drop characteristics of R600a, R1234ze(E), and a mixture of R1234ze(E)/R32 have been reported by Qiu *et al.* [10]. The results from 8 mm tube were obtained at 20 °C saturation temperature, heat flux was in 5-10 kW/m^2 range whereas the mass flux was within 200-400 kg/m^{2}s. The HTC were reported to increase with an increase in heat flux whereas a slight effect of mass flux was also reported. The similar trends were reported for all tested fluids. The R1234ze(E) showed about 33% less values for HTC than R600a whereas R600a showed about 18% less values than tested mixture.

A detailed experimental investigation on flow boiling heat transfer of R600a was reported by Yang *et al.* [11]. The experiments were conducted for a range of saturation pressures (0.215-0.415 MPa) for different mass fluxes (67-194 kg/m^{2}s) with 10.6-194 kW/m^2 heat flux. The Liu and Winterton correlation [12] was reported to have good agreement with experimental data with a mean absolute error (MAE = 11.5%). The results showed that HTC were unaffected from mass flux when vapor quality was less than 0.1. The heat transfer results were reported to be primarily influenced by nucleate boiling (NB) and no significant effect of mass flux was observed, while NB prevails by increasing heat flux.

Flow boiling heat transfer characteristics of H_2O at a system pressure of 200 kPa in a horizontal tube of 2.98 mm diameter, mass flux ranging from 50-200 kg/m^{2}s, and ambient inlet temperature of 80 °C were investigated by Yu *et al.* [13]. The analysis of experimental data on heat transfer of H_2O in compact channel showed strong influence of heat flux whereas the same was unaffected by mass flux. The observed trends were explained with domination of NB mechanism over the convective heat transfer mechanism for vapor quality below 0.5.

Flow boiling characteristics of pure refrigerant R600a and its comparison with R-134a were investigated experimentally in 2.6 mm ID tube and reported in [14]. The HTC were assessed for a range of mass flux (240-440 kg/m^{2}s), heat flux (10-160 kW/m^2), and vapor quality (0-0.9) at saturation temperature of 22 ºC. The experimental campaign showed that HTC of R600a were influenced by heat flux at lower quality regions. But for high mass flux and vapor quality this effect diminishes. The experimental data was well predicted with Kim and Mudawar [15] correlation with root means square (RMS) error of about 24% for both refrigerants.

Literature surge has shown many macro and micro scale correlations for prediction of boiling HTC. The correlations are mainly based on curve fitting of experimental data and cannot be extrapolated beyond their development range. Many researchers [16-26] reported on prediction capabilities of existing micro and macro scale correlations. Still there is no unified and reliable correlation model that can accurately predict boiling HTC in compact channels. Lack of precise prediction mechanisms of heat transfer appealed researchers to gather a diverse and wide range of data for compact channels with a focus on developing a better understanding of control mechanisms and assessment methods.

Keeping in view of recent demands for environmental benign medium, this study is focusing on flow boiling heat transfer characteristics of low GWP refrigerants. Low GWP refrigerants from HFC, HFO, and natural family (R152a, R1234yf, and R600a) were selected and their thermal performance was compared with conventionally used HFC R134a. The experimental data reported here was traced from earlier studies from the literature [27-29], the data was explored to clarify the effect of operating parameters (heat flux, mass flux, vapor quality, operating pressure, operating medium) and prediction assessment for correlations from the literature.

Experimental set-up

The experimental data presented in this paper has been collected from earlier studies [27-29] reported in the literature. In all cases experiments were conducted with pure refrigerants R134a, R152a, R600a, and R1234yf using a vertical mini channel (inner diameter 1.60 mm and 245 mm heated length) under upward flow conditions. The operating conditions are summarized in tab. 1. The details on equipment, instrumentation and operating scheme are not duplicated here and interested readers are referred to [27-30].

Table 1. Experimental conditions for flow boiling heat transfer (ID = 1.60 mm and L_h = 245mm)

Refrigerants	Data source	Saturation temperatures [ºC]	Mass velocity [kgm^{-2}s^{-1}]	$\Delta t_{sub,in}$ [K]	x [–]	R_a [µm]
R134a	[28]	27 and 32	100-500	1-1.5	Until dryout	0.95
R152a	[27]	27 and 32	100-500	1-1.5	Until dryout	0.95
R600a	[29]	27 and 32	50-350	1-1.5	Until dryout	0.95
R1234yf	[28]	27 and 32	100-500	1.1.5	Until dryout	0.95

Single phase theory on heat transfer and fluid-flow is well developed and this was used to validate the test set-up, experiments were carried out to evaluate heat transfer and pressure drop characteristics under single phase conditions. Experimental findings matched well with well known models Gnielinski correlation [31] and Blasius Correlation [32] (for heat transfer and pressure drop characteristics) and thus validated the proper functionality of the test set-up.

All tests were conducted under heat flux controlled conditions and data was recorded for stable operating conditions and with a gradual increase of heat flux. In all cases subcooled inlet conditions were maintained and data was collected till completion of dryout in the test section, dryout incipience was noticed with a sharp increase in the wall temperature of test section near the outlet of test section. The REFPROP 9 [33] developed by NIST was utilized for the estimation of property data for all four refrigerants.

The surface morphology of the heating surface has a significant effect on the bubble nucleation process and this in turns controls the heat transfer performance. The inner surface of the test section was therefore, scanned using Talysurf PGI 800 to evaluate the roughness profile of the heating surface. The average roughness value, R_a, was noticed to be 0.95 μm.

Data reduction

Thin-walled stainless steel tube was used as a test piece for the data reported in this study. Electricity (direct current supply) was used to heat the test piece using Joule's heating effect, injected heat flux was estimated using the following equation:

$$q'' = \frac{VI}{A_\mathrm{h}} = \frac{VI}{\pi d_i l_\mathrm{h}} \tag{1}$$

where V and I were supplied voltage and current, respectively and A_h was the heated area.

Outer wall temperatures were recorded by fixing thermocouples on outer surface of the test object using a thermally conductive epoxy. The temperature on inner wall surface at any specific location was evaluated with measured external wall temperature using 1-D conduction, eq. (2), approach with generation of heat in the cylinder:

$$t_{\mathrm{wallin},\,z} = t_{\mathrm{wallout},z} + \frac{Q}{4\pi k l_h}\left[\frac{\varphi\left(1-\ln\varphi\right)-1}{\varphi-1}\right] \tag{2}$$

where $t_{\mathrm{wall\ in},z}$ and $t_{\mathrm{wall\ out},z}$ represents inner and outer wall temperatures, respectively whereas, $\varphi = (d_\mathrm{out})^2/(d_\mathrm{h})^2$ and $Q = VI$ is heating power.

The bulk fluid temperature at any axial location along the test piece was estimated with measured inlet temperature and heat added to the test set-up using:

$$t_{\mathrm{fluid},z} = t_\mathrm{in} + z\frac{q''\pi d}{\dot{m}C_p} \tag{3}$$

The local HTC at any location, z, was calculated:

$$\alpha_z = \frac{q''}{t_{\mathrm{wallin},\,z} - f_{\mathrm{fluid},z}} \tag{4}$$

Vapor quality at any vertical position was determined using inlet conditions and heat injected in the test set-up:

$$x_z = \frac{q''\pi d\left(z - z_o\right)}{A_c G h_{lg}} \tag{5}$$

where z_o is the point where the saturated conditions along the experimental section were approached. The point where boiling initiated was estimated:

$$z_o = \frac{\dot{m}C_p\left(t_\mathrm{sat} - t_\mathrm{in}\right)}{q''\pi d} \tag{6}$$

where h_{lg} is enthalpy of vaporization and z-z_o is boiling length.

Analysis of experimental uncertainties

The credibility and quality of any measured or computed parameter is reflected by its associated level of uncertainty. For this study B-type uncertainty in calculated parameters was estimated by using propagation of error method as suggested by Moffat [34] and Holman

[35]. The accuracy of measuring instruments (pressure sensor, temperature sensor, mass-flow meter, multimeter) was used in conjunction with the fore stated error propagation method for estimation of uncertainty in the calculated parameters (heat flux, mass flux, vapor quality, HTC, *etc.*). The degree of uncertainty in measured and calculated parameters is summarized in tab. 2.

Table 2. Uncertainties in measured and calculated parameters

Parameters	Equipment specification	Maximum Uncertainty
Inside diameter	1.60 mm	±0.007 mm
Absolute pressure	PDCR 4060 (0-20 bar)	±10 mbar
Differential pressure	PTX 5072 (0-500 mbar)	±1 mbar
Mass-flow rate	Micro-motion DS006	±3%
Wall temperature	T-type thermocouples	±0.1 °C
Saturation temperature	*T*-type thermocouples	±0.2 °C
Electricity input	Manson SPS-9600 (0-60 A)	±1% + 1 count
Heat flux density		±4%
Heat transfer coefficient		< ±14% (for $q'' > 10$ kW/m^2)
Vapor quality		±7%

Results

This segment contains a discussion on the analysis of data collected from flow boiling experimental campaigns, details of operating conditions for all tested mediums are given in tab. 1. Thermal performance of any thermo-fluid system relies significantly on thermophysical properties of heat transfer fluid (HTF), three primary characteristics that distinguish mediums from one another are liquid viscosity, interfacial surface tension, and vapor density.

Thermophysical properties for four tested refrigerants are briefly discussed in the start, this follows details on the effect of operating parameters (heat flux, mass flux, saturation temperature, vapor quality, operating medium) on boiling heat transfer performance whereas assessment of prediction methods is given at the end.

Thermophysical properties

Thermal response of any HTF is mainly controlled by its thermophysical properties. From heat transfer perspective, higher thermal conductivity, low surface tension, and viscosity are the desired characteristics [36-40]. Thermophysical properties for R152a, R600a, and R1234yf were compared with R134a, and contrast is shown in fig. 1**.

Thermophysical properties of tested refrigerants at 27 °C and 32 °C saturation temperature were analyzed in detail. Refrigerants R600a and R152a have a higher heat of vaporization and surface tension than R134a while R1234yf has a lower heat of vaporization and surface tension. It is noted that an increase in saturation pressure reduces latent heat of vaporization, surface tension, thermal conductivity, and liquid density for all refrigerants (R134a, R152a, R600a, and R1234yf). Fluids generally show higher heat transfer coefficients at high saturation pressure and low viscosity, such results were reported in the literature by Basu *et al.* [41] and Pamitran *et al.* [42]. The fluids having good liquid-flow properties keep the heating surface

** Computed at mass flux = 500 kg/m^{2}s ang heat flux = 50 kW/m^2, whereas Bd, Bo, P, P_red, and Prandtl are Bond numbers, boiling number, system pressure, reduced pressure and Prandtl number

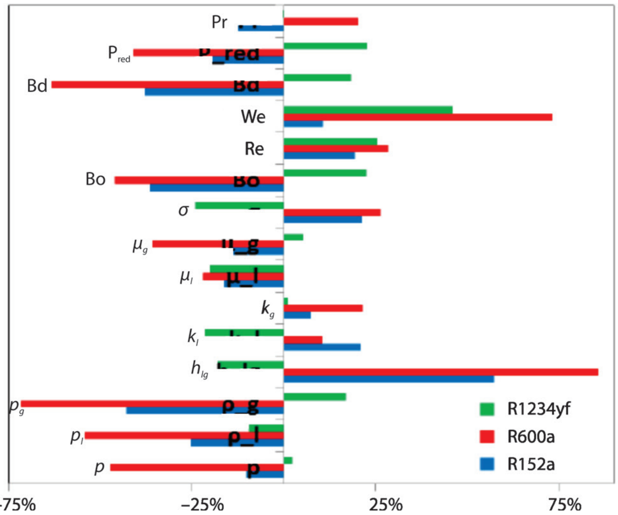

Figure 1. Thermophysical properties and dimensionless numbers

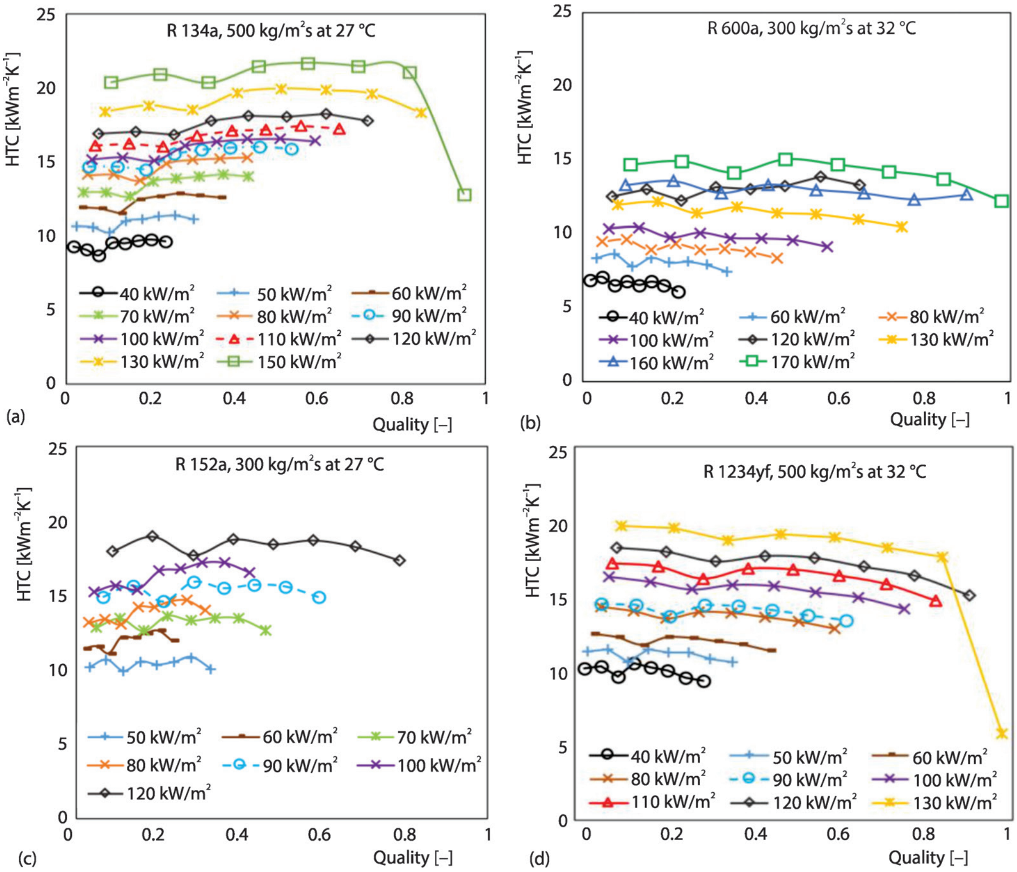

Figure 2. Variation of local heat transfer coefficients with vapor quality: (a) for R134a, (b) for R600a, (c) for R152a, and (d) for R1234yf

wet and hence dryout delayed at high vapor quality regions. The major concern on selection of R152a and R600a as a suitable replacement for R134a is their high flammability [37].

Effect of heat flux on boiling heat transfer

The effects of heat flux on the HTC, are shown in figs. 2(a)-2(d). All experiments were carried out with a gradual increase of heat flux and continued till completion of dryout of the medium in the test section. The figure set shows data for all four tested mediums, it is clearly visible that heat transfer was significantly affected with heat flux whereas the effect of vapor quality appeared to be insignificant for conditions before incipience of dryouts ($x \geq 0.8$) in the test section.

In all cases a dip in HTC at third thermocouple location was noticed, this was believed to be due to poor connection of this thermocouple with the test tube. Similar trends (strong influence of heat flux and insignificant effect of vapor quality) were noticed at other operating conditions (mass fluxes and saturation temperatures).

Effect of mass flux

A variable speed pump was used for fluid circulation through the test loop, the fluid mass-flow rate was controlled with the variation of the operating speed of this pump. The effect of mass velocity/flux on heat transfer performance is clarified in fig. 3, where local heat transfer coefficients for different mass velocities are plotted against vapor quality. All other operating conditions (heat flux, saturation temperature) were maintained to track the effect of mass flux. As is clear from fig. 3 that different mass velocities duplicated similar HTC so in this case heat transfer was not influenced by mass flux and vapor quality.

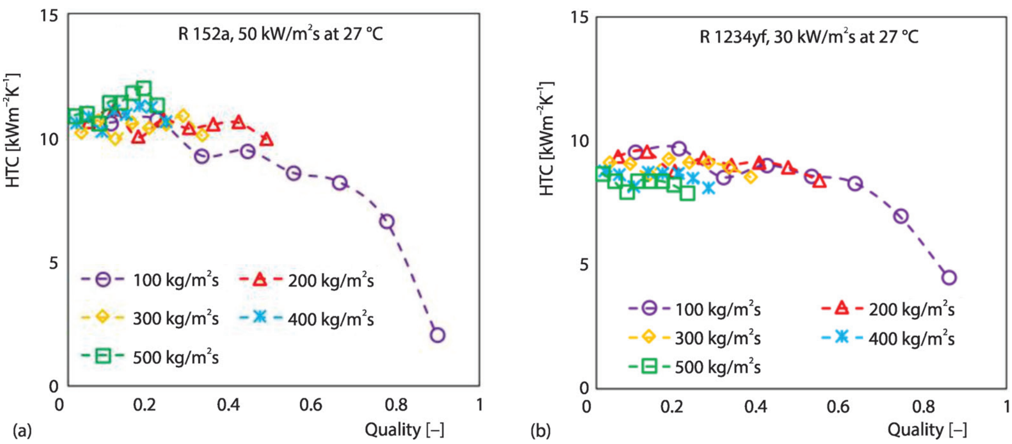

Figure 3. Effects of mass flux on local HTC 5 for R152a and R1234yf

Similar trends were noticed with other tested mediums for this study. A significant drop in HTC at high vapor quality is believed due to incipience of dryout in the test section, this was further confirmed with a sharp increase in wall temperature. Such trends (strong dependency on heat flux with the insignificant effect of mass velocity) have been explained in the literature [43-45] with the dominance of the nucleate boiling mechanism.

Effect of saturation pressure on heat transfer

Figure 4 shows the effect of saturation pressure on HTC. In all cases experimental data was collected at two operating pressures corresponding to 27 °C and 32 °C saturation temperature and all other operating conditions (heat flux, mass flux) remained fixed to clarify the effect of saturation temperature. For all tested mediums (R134a, R1234yf, R152a, and R600a) HTC increased with an increase in operating pressure level. This is due to the fact that an increase in pressure reduces bubble departure diameter and speeds up bubbles escape velocity which in turn causes enhancement of heat transfer. The increase in pressure also reduces surface tension, viscosity, and density of HTF. It is speculated that the aforementioned characteristics have positively affected fluid's thermal performance. For this study, experimental data was collected with a limited range of variation in operating pressure levels however the findings are consistent with many studies reported in the literature [46, 47].

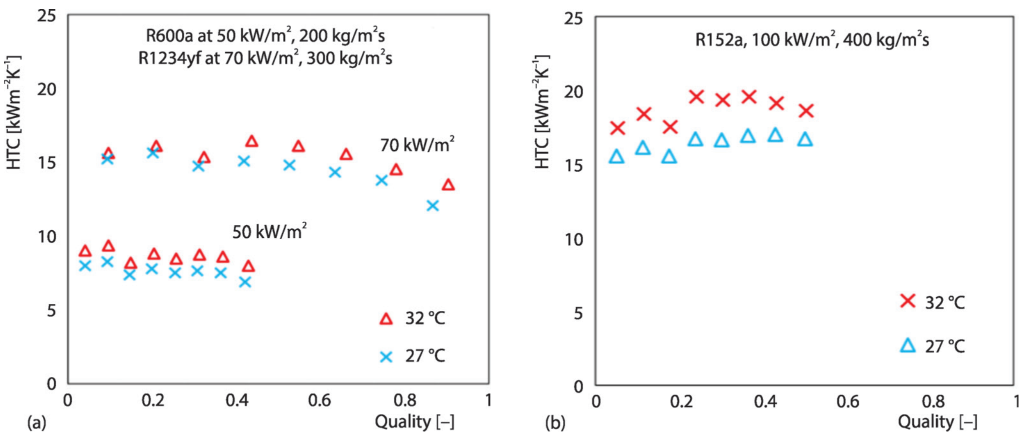

Figure 4. Effect of saturation temperature on HTC

Effect of working medium

Variation of local HTC with vapor quality for four tested refrigerants of this study is shown in fig. 5. The data was collected under similar operating conditions (operating pressure, heat flux, mass flux, and vapor quality) to clarify HTC of reported mediums. Almost similar results (within the stated degree of uncertainty in experimental results) for HTC were noticed with R134a, R152a, and R1234yf whereas R600a showed significantly lower values. The HTC of any HTF is mainly controlled by its thermophysical properties, R600a has lower vapor density and higher surface tension compared with the other three tested mediums reported in this study. The R152a and R600a have significantly higher latent heat of vaporization than R134a and R1234yf, these fluid can tolerate higher heat fluxes.

Assessment of correlations

The collected experimental data was compared with renowned correlation from the literature. Figure 6 graphically shows the result for this comparison exercise whereas correlation definition and summary of assessment are given in tab. 3. Two statistical parameters, MAE, and percentage of data predicted within ±30% were considered for this assessment. The MAE accounts for errors between anticipated and empirical data and it is computed:

$$MAE = \frac{1}{N}\sum_{j=1}^{N}\left|\frac{h_{\text{predicted}_j} - h_{\text{experimental}_j}}{h_{\text{experimental}_j}}\right| \times 100$$

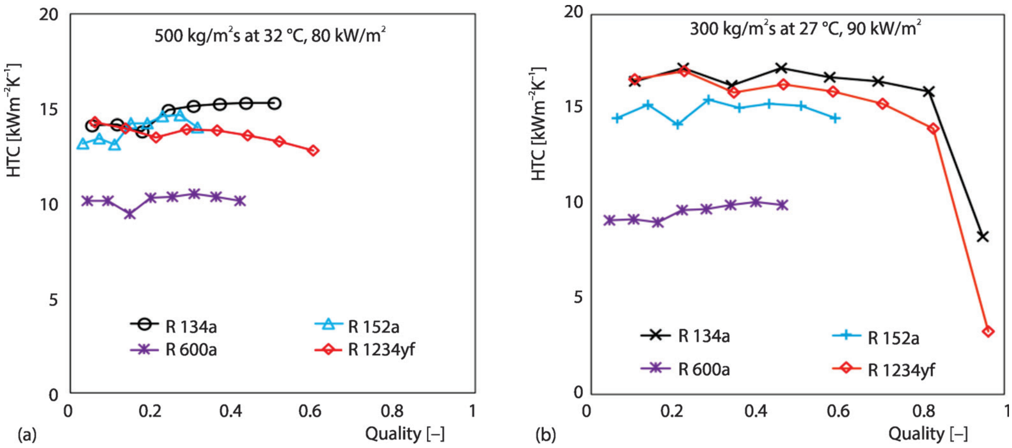

Figure 5. Variation of local HTC with vapor quality

It should be mentioned that data points before the start of boiling and after incipience of dryout were excluded in comparison exercise as correlations are developed to cover the boiling region only.

As HTC were strongly controlled by heat flux and saturation temperature (commonly reported as the dominance of NB in the literature) therefore, experimental data was compared with predictions made by Cooper's pool boiling correlation [22]. The comparison revealed that this correlation mostly underpredicted experimental data for tested mediums, isobutane was an exception which showed overprediction results fig. 6(a). The assessment showed that correlation predicted 57.40% of experimental data within ±30% error band at a MAE value 28.04%. More reasonable predictions were noticed with changing the leading multiplier of this correlation.

The micro-scale correlation from Tran *et al.* [7] shown in fig. 6(b) consistently underpredicted experimental data for all four refrigerants with MAE value of 28.44% and 54.67% data within ±30 total error band. The correlation was originally developed from a limited data set (for R12 and R113 in ≤ 3 mm diameter tube) and it seems that it does not show good predictions when tested for broader operating conditions.

The micro and macro scale model from Mikielewicz and Gungor and Winterton [18, 25] showed a large discrepancy with experimental data with MAE value of 28.68% and 21.57%, respectively as shown in figs. 6(c) and 6(d). At low heat fluxes these models predict data well while at high heat fluxes mostly under-predicted the data. Gungor and Winterton correlation uses Dittus-Boelter correlation [48] for prediction of convective boiling contribution, it seems that the convective boiling enhancement term could not be properly predicted with this model.

The experimental findings were also compared with Lazarek and Black [9] correlation as shown in fig. 6(e). This correlation was developed from R113 based database collected from a channel of 0.3 cm diameter where NB was reported to be the dominant mechanism. The analysis of our database showed that results for heat transfer were over anticipated at high thermal fluxes. Overall correlation predicted 76.63% of data with MAE value of 21.89% within ±30% error range.

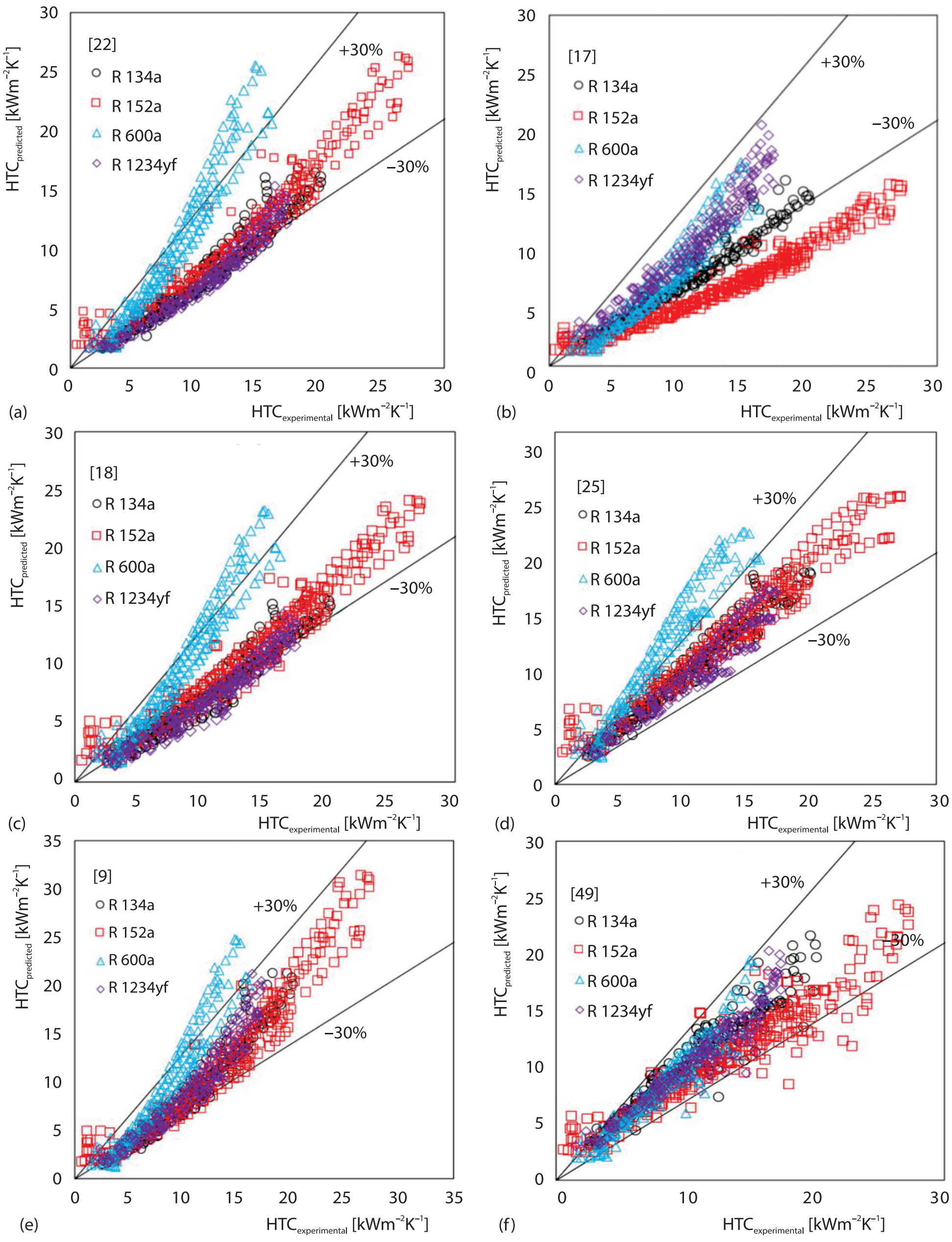

Figure 6. Comparison of micro/macro scale correlation with experimental data; (a) [22] , (b) [7], (c) [18], (d) [25], (e) [9], and (f) [49]

Among all tested correlations, Mahmoud and Karayiannis [49] correlation, fig. 6(f), showed better prediction for all four refrigerants (R134a, R152a, R600a, and R1234yf), the correlation predicted 93.69% experimental data with MAE 14.17% in ±30% error band range.

This correlation was developed with a regression analysis of the R134a dataset collected under wide operating conditions.

Table 3. Summary of statistical assessment of correlations

Correlation	Mathematical formulations	*MAE* [%] of data ±30%
[22]	$\alpha = 55 p_r^{0.12-0.4343 lnR_a} \left(-0.4343 \ln p_r\right)^{-0.55} M^{-0.55} q''^{0.67}$	28.07/57.40
[9]	$\alpha = 30 \mathrm{Re}_{lo}^{0.857} \mathrm{Bo}^{0.714} \dfrac{k_l}{d_i}$	21.89/76.63
[49]	$\alpha_{tp} = 3320 \dfrac{\mathrm{Bo}^{0.63} \mathrm{We}_l^{0.2} \mathrm{Re}_l^{0.11}}{\mathrm{Co}^{0.6}} \dfrac{k_l}{d}$	14.17/93.69
[7]	$\alpha = 840000 \left(\mathrm{Bo}^2 \mathrm{We}_l\right)^2 \left(\dfrac{\rho_l}{\rho_g}\right)^{-0.4}$	28.44/54/67
[25]	$\alpha = E\alpha_{D-B} + S\alpha_{\mathrm{cooper}}$ $E = 1 + 24000 \mathrm{Bo}^{1.16} + 1.37 \left(\dfrac{1}{X_{tt}}\right)^{0.866}$ $S = \left(1 + 1.15 \cdot 10^{-6} E^2 \mathrm{Re}_l^{1.17}\right)^{-1}$	21.57/77.78
[12]	$\dfrac{h_{tp}}{h_{lo}} = \sqrt{\varphi''_{MS} + \dfrac{1}{1+p} + \left(\dfrac{h_{nb}}{h_{lo}}\right)^2}$ $p = 0.00253 \mathrm{Re}_{lo}^{1.17} \mathrm{Bo}^{0.6} \left(\varphi''_{MS} - 1\right)^{-0.65}$ $\varphi''_{MS} = \left[1 + 2\left(\dfrac{1}{f_1} - 1\right) x \mathrm{Co}^{-1}\right] (1-x)^{1/3} + \dfrac{x^3}{f_2}$ $h_{\mathrm{nb}} = h_{\mathrm{cooper}}$	28.68/63.08

Conclusions

This paper presented a detailed investigation on boiling HTC for three low GWP refrigerants (R1234yf, R600a, and R152a) where the performance was benchmarked against conventionally used R134a. The detailed parametric effects were investigated and experimental data were compared with predictions of renowned micro and macro-scale correlations from the literature. Main findings from the study are summarized as follows.

- Flow boiling heat transfer in the tested channel (1.60 mm diameter tube) was strongly influenced by heat flux and saturation pressure level whereas an insignificant effect of mass flux and vapor quality was noticed. Heat transfer coefficients increased with an increase in satu-

ration temperature. The experiments were done in a narrow range of operating conditions, a wider range should be tested to confirm influence of saturation temperature.
- Under similar operating conditions R600a shows lower heat transfer performance compared to the other three tested mediums (R152a, R600a, and R1234yf), this is due to the difference in thermophysical properties of tested mediums.
- The R152a and R1234yf showed comparable thermal performance and thus could be better possible replacement candidates for replacing R134a, further experimentations on their miscibility with oils needed to confirm true behavior under real operating conditions.
- Among selected prediction methods, the correlation proposed by Mahmoud and Karayannis [49] predicted data with reasonably good predictions. The correlation predicted over 90% of data within ± 30% with14.17% MAE.

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