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Muhammad Shujaat Ali
University of Engineering and Technology, Lahore

Zahid Anwar
University of Engineering and Technology, Lahore

M. A. Mujtaba
University of Engineering and Technology, Lahore

Manzoore Elahi M. Soudagar
Universiti Malaya

Irfan Anjum Badruddin
King Khalid University

See next page for additional authors

Authors

Muhammad Shujaat Ali, Zahid Anwar, M. A. Mujtaba, Manzoore Elahi M. Soudagar, Irfan Anjum Badruddin, Mohammad Reza Safaei, Asim Iqbal, Asif Afzal, Luqman Razzaq, Abdulqhadar Khidmatgar, and Marjan Goodarzi

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Muhammad Shujaat Ali [a], Zahid Anwar [a], M.A. Mujtaba [a,b], Manzoore Elahi M. Soudagar [b], Irfan Anjum Badruddin [c,d], Mohammad Reza Safaei [e,f], Asim Iqbal [a], Asif Afzal [g,k], Luqman Razzaq [a], Abdulqhadar Khidmatgar [h], Marjan Goodarzi [i,j,*]

[a] Department of Mechanical, Mechatronics and Manufacturing Engineering (New Campus), University of Engineering and Technology Lahore, Pakistan
[b] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia
[c] Research Center for Advanced Materials Science (RCAMS), King Khalid University, P.O. Box 9004, Abha, 61413, Asir, Saudi Arabia
[d] Mechanical Engineering Department, College of Engineering, King Khalid University, P.O. Box 394, Abha, 61421, Saudi Arabia
[e] Division of Computational Physics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[f] Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[g] Department of Mechanical Engineering, P. A. College of Engineering (Affiliated to Visvesvaraya Technological University, Belagavi), Mangaluru 574153, India.
[h] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, 43400, Malaysia
[i] Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan
[j] Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80259, Jeddah, Saudi Arabia
[k] International Research Establishment for Energy and Environment (IREEE), Vallikunnam, Alappuzha, Kerala 690501, India

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ABSTRACT

Environmental concerns have urged a search for eco-friendly refrigerants in the refrigeration industry to overcome ozone depletion and global warming problems. Therefore, current research emphasizes frictional pressure drop during flow boiling of environment-friendly refrigerants (GWP<150), isobutane, HFC-152a, HFO-1234yf were tested against commonly reported HFC-134a. The data presented here was collected under heat flux-controlled conditions; the test piece was a round tube (1.60 mm diameter). The data collection was performed at 27 and 32 °C with mass velocities in 50–500 kg/m^{2}s range. Effects of critical controlling parameters, like heat flux, mass velocity, exit vapor quality, operating pressure and medium, were studied in detail. It was observed that pressure drop increases along with mass velocity increment in the test piece and increases with exit vapor quality increment. The same was noticed to decrease with saturation temperature increment. Parametric effects and prediction of assessment methods are reported.

* Corresponding author. Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan.
E-mail addresses: me.soudagar@gmail.com (M.E.M. Soudagar), cfd_safaei@tdtu.edu.vn (M.R. Safaei), mgoodarzi@lamar.edu (M. Goodarzi).

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Nomenclature

D_i	Inner diameter of test section (mm)
G	Mass flux (kg/m^2s)
I	Current applied (A)
K	Thermal conductivity (W/mk)
$\dot{m}$	Mass flow rate (kg/s)
q''	Heat flux (W/m^2)
T_s	Saturation temperature (°C)
X	Vapor quality (−)

CRediT author statement

Muhammad Shujaat Ali: Methodology, Writing-Original Draft, Review & Editing, Investigation, and Formal analysis. Zahid Anwar: Supervision, Resources, Writing-Original Draft, Review & Editing. MA Mujtaba: Supervision, Methodology, Conceptualization. Manzoore Elahi M Soudagar: Review & Editing and Formal analysis. Irfan Anjum Badruddin: Review & Editing and Funding. Marjan Goodarzi and Mohammad Reza Safaei: Project administration and Supervision. Asim Iqbal, Luqman Razzaq, Abdulqhadar Khidmatgar and Asif Afzal: Formal analysis, Review & Editing.

Abbreviations

SS	Stainless steel
CHF	Critical heat flux (W/m^2)
DPS	Differential pressure sensor
EES	Engineering equation solver
FPD	Frictional pressure drop
GWP	Global warming potential
MAE	Mean absolute error (%)
ODP	Ozone depletion potential

Greek letter

σ	Surface tension

Subscripts

P_d	Pressure drop
T_p	Two-phase

Dimensionless Group

Bd	Bond No $\left[\frac{q'}{G.h.l.g}\right]$
Co	Confinement No $\left[\sqrt{\frac{\sigma}{g(\rho_l-\rho_g)d^2}}\right]$
Eo	Eotovs No $\left[\frac{(\rho_l-\rho_g)gd^2}{8\sigma}\right]$

1. Introduction

Conventional refrigerants are typically having higher global warming potential (GWP) and ozone depletion potential (ODP). Furthermore, they have a long life and stay for years when leaked from a refrigeration/air conditioning system. Recently researchers across the globe are in search of environmentally benign refrigerants. Legislators worldwide are also forcing to minimize the use of a compound with high GWP and ODP [1]. Fortunately, a family of natural refrigerants (hydrocarbons, ammonia, CO_2) and some eco-friendly synthetic alternatives (like HFC-152a, HFO-1234yf and many others) exists. The forestated compounds have favorable thermodynamic properties and are compatible with commonly used materials in the industry [2]. The utilization of eco-friendly refrigerants will safeguard the environment from refrigerant-related environmental deterioration, which will help clean the environment [3–5].

The heat transfer process involves diverse application areas like refrigerators, heat pumps, thermal power plants, nuclear reactor, etc. [6–8]. Compact devices are now increasingly being employed due to their equivalent (in some cases even better) hydrothermal performance and better space utilization capabilities. Compact heat exchangers offer a significantly high surface area to volume of flowing fluid and can handle significantly high heating/cooling demands [9–11]. The utilization of such compact channels and gadgets

Table 1
Properties of natural refrigerants.

	R134a	R152a	R600a	R1234yf
Chemical Formula	CF_3 CH_2 F	$C_2H_4F_2$	C_4H_{10}	$C_3H_2F_4$
ODP	0	0	0	0
GWP	1430	124	3	4
Density	0.00425 g/cm^3	2.7 g/cm^3	2.51 kg/m^3	1.1 g/cm^3
Molar mass	102.03 g/mol	66.05 g/mol	58.12 g/mol	114 g/mol
Boiling point	−26 °C	−25 °C	−11.7 °C	−30 °C
Class	A-1	A-2	A-3	A-1

A-1 = Non-flammable, A-2 = Flammable with low burning velocity, A-3 = Highly flammable.

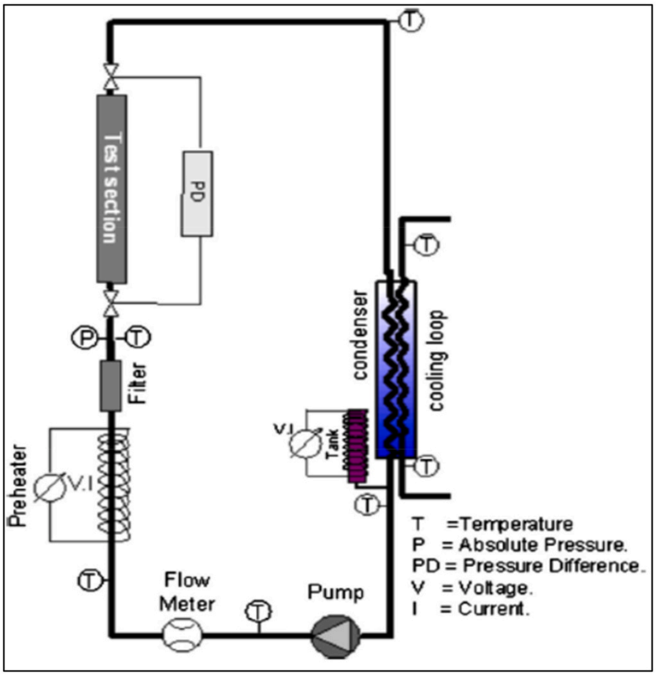

Fig. 1. Schematics of the apparatus [35].

equipped with them also reduces the mandatory material cost and fluid charge to survive high heat flux [12–14]. Two-phase (boiling/condensation) flow conditions are further helpful in improving the potential to withstand high heat flux (>100 kW/m^2) and better control of local hot spots [15,16]. As the channel squeezes viscous effect also increases. Thus, more pumping power would be required for fluid circulation in compact channels [17,18]. Although the literature is bombarded with information regarding the phase change heat transfer process, compact channel's transport process yet needs to be explored for better apprehension [19–21]. More research work is needed to clarify the transport processes' current understanding in mini/microchannel. Table 1 below provides a quick summary of refrigerant properties.

Thermo-fluid system design requires reliable information of two-phase FPD in the system under consideration [22,23]. Overall thermal performance of device handling two phase conditions has a dependence on system's operating pressure [24]. Therefore, a precise measurement of frictional pressure drop is essential for defining the two-phase system's proper operating conditions [25]. Refrigerant condensation was analyzed by Jige et al. [26] via horizontal conduit using mini/micro-channels. At 40–60 °C, Heat transfer performance and pressure drop were analyzed for refrigerants. The critical controlling parameters for condensation were reported to be mass velocity, quality and operating medium. A correlation was proposed, and it can be used for estimation of condensation pressure drop analysis in mini-channels configuration.

Maqbool et al. [27] worked on propane's pressure drop and boiling heat transfer characteristics via 1.70 mm diameter utilization. The tests were carried out at different temperatures where applied heat flux was in 4–275 kW/m^{2}s range. The tested mass velocity was within 95 and 490 kg/m^2. Consequently, frictional pressure drop increment was observed along with vapor quality and mass flux.

Kim and Mudawar [28] suggested a method to predict two-phase frictional pressure drop during flow boiling. The catalog consisted of nine working fluids, and the diameter of the channels was within 0.349–5.35 mm. The exit vapor content was between 0 and 1, while the mass velocity was 33–2738 kg/m^{2}s. The proposed correlation predicted data reasonably well with 17.22% MAE.

R448A's two-phase heat transfer and pressure drop was examined by Lillo et al. [29]. They employed 6 mm internal diameter single

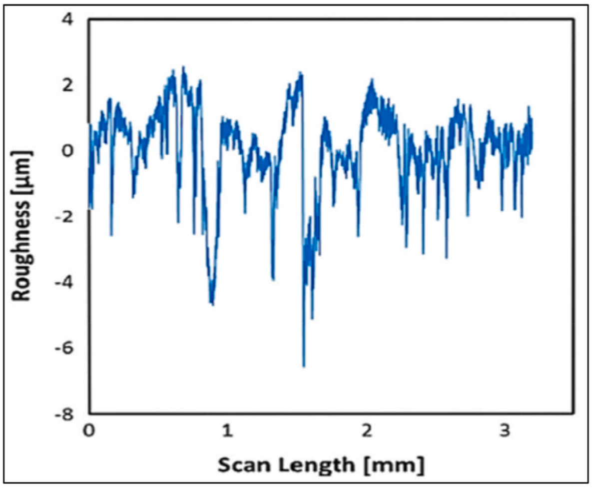

Fig. 2. Roughness profile for test object's heating surface [39].

Table 2
Details on operating conditions for pressure drop tests.

Refrigerants	Diameter	Heated Length	T_s	Mass Flux	$\Delta t_{sub,in}$	X	Ra
	[mm]	[mm]	[°c]	[kg/m^{2}s]	[K]	[−]	[µm]
R1234yf	1.60	245	27,32	100–500	1–1.5	Until dryout	0.95
R134a	1.60	245	27,32	100–500	1–1.5	Until dryout	0.95
R152a	1.60	245	27,32	100–500	1–1.5	Until dryout	0.95
R600a	1.60	245	27,32	50–350	1–1.5	Until dryout	0.95

tube manufactured via AISI 316 stainless steel. Temperature range from 23.3 °C to 56 °C and from 146 to 601 kg/m^{2}s varying mass flux was reported. Some authors performed a comparative analysis of heat transfer coefficient and pressure drop relative to the conventional R404A refrigerant mixture by maintaining both cases' operating conditions.

They reported that the correlation of Gungor and Winterton [30], and Friedel [31] showed good predictions for their data.

Khalid et al. [32] studied the various techniques for improving thermal performance in heat pipes.

By employing some innovative measures, heat pipe's thermal performance can be enhanced. According to researchers, several techniques can be employed to enhance the heat pipe's thermal performance. However, thermal performance can be decreased by employing nanofluids in heat pipes.

Water and TiO_2–H_2O nanofluids were utilized by Tariq et al. [33] to examine thermal performance along with 0.005% and 0.01% volumetric concentration. Standard and mini channel heat sink thermal performance was examined comparatively. The normal-channel heat sink was three and half times cheaper relative to the mini-channel heat sink. A prominent pressure drop was noticed in a normal-channel relative to a mini-channel heat sink.

The literature review has shown limited information regarding the two-phase frictional pressure drop for eco-friendly refrigerants, specifically for tests conducted with mini-channels. Legislators worldwide (like EU F-gas regulation) are now asking to phase out mediums having high GWP. With this paper, an effort is made to add a reliable data set and extend the current understanding of two-phase frictional pressure drop of low GWP refrigerants (R1234yf, R152a, and R600a). It is further clarified that the data presented in this paper was collected from boiling experimentation campaigns carried out at Royal Institute of Technology KTH, Sweden, heat transfer results were already published [34–38]. In contrast, pressure drop conclusions are demonstrated within the current paper. Performed experimentations were under heat flux-controlled conditions. The effect of operating parameters and the prediction method's analysis regarding pressure drop is reported in the current paper.

2. Experimental setup

A closed-loop refrigerant flow scheme via heating and cooling arrangements has been used as a test apparatus. The setup's conceptual diagram is shown in Fig. 1. 1.6 mm internal diameter and 290 mm long stainless-steel tube was employed as a testing specimen. The apparatus was designed so that crucial operating conditions (heat and mass flux, system pressure, flow rate) could be independently controlled. The operating details are not duplicated here, and interested readers may track such details from earlier publications on heat transfer [34–38]. All tests reported here were carried out under upward flow conditions.

The surface roughness positively affects the bubble formation process. The process of bubble nucleation controls the overall heat transfer performance. In order to scan the heating surface roughness profile, conical stylus profilometry was utilized. Heating surface

Table 3
T_p mixture viscosity models utilized in Homogenous Equation.

Author(s)	Equation
McAdams et al.{McAdams, 1942 #27}	$\mu_m = [(1\text{-}x/\mu_l)+(x/\mu_g)]^{-1}$
Akers et al.{Akers, 1958 #26}	$\mu_{tp} = \mu_f\ [(1\text{-}x) + x\ (\mu_l/\mu_g)]^{-0.5}$
Cicchitti et al. {Cicchitti, 1959 #29}	$\mu_{tp}=(1\text{-}x)\mu_l + x\mu_g$
Owens{Owens, 1961 #30}	$\mu_{tp} = \mu_l$
Dukler et al.{Dukler, 1964 #31}	$\mu_{tp}=(1\text{-}x)\mu_l + x\mu_g$
Beattie and Whalley{Beattie, 1982 #32}	$\mu_{tp} = \mu_g\omega + (1\text{-}\omega)\ (1 + 2.5\omega)\mu_f$
Lin et al.{Lin, 1991 #33}	$\mu_{tp} = \mu_l\mu_g\ [\mu_g + x^{1.4}\ (\mu_l\text{-}\mu_g)]^{-1}$

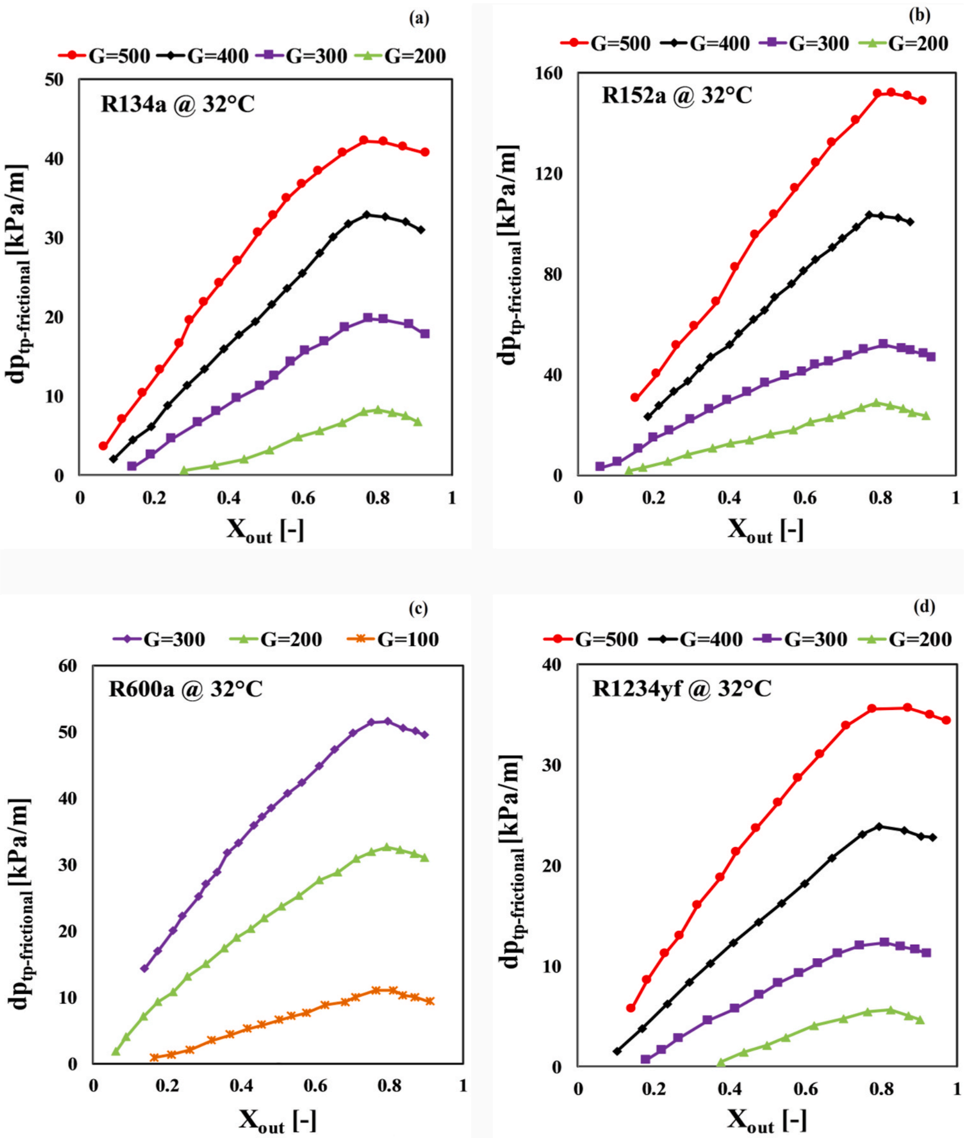

Fig. 3. Effect of mass flux and vapor quality at t_{sat} = 32 °C for (a) R134a, (b) R152a, (c) R600a, and (d) R1234yf (for all cases G is in kg/m^2s).

roughness profile findings are demonstrated in Fig. 2. The average determined roughness (Ra) value is 0.95 μm.

The setup was validated by conducting single-phase tests. As single-phase theory is well developed and accepted. So heat transfer and pressure drop results collected from test setup were compared with well-known correlations, and this has shown good agreement among the two, which validated the operational functionality of the test loop. The details on data collection for this study are given in Table 2.

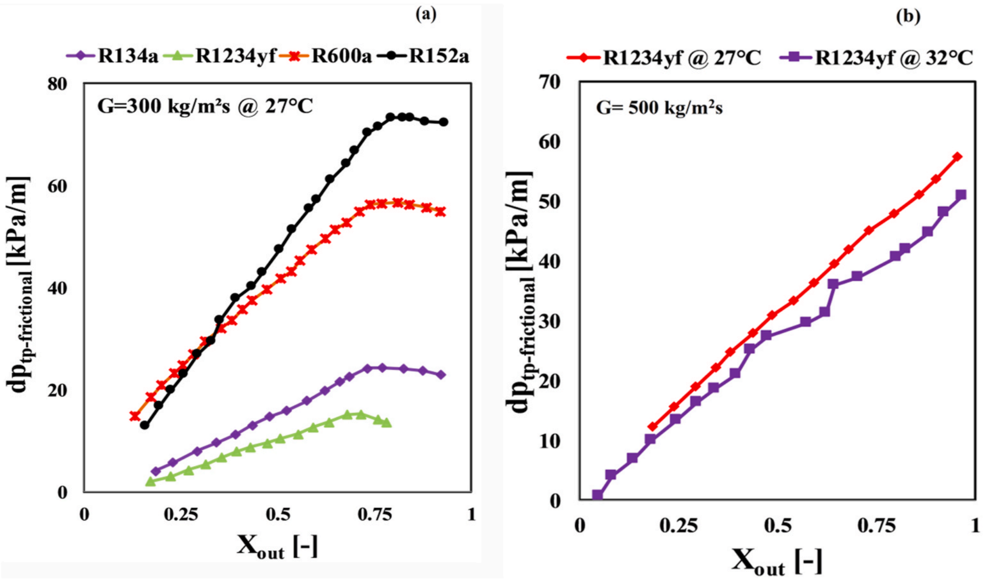

Fig. 4. Two-phase frictional pressure drop for different refrigerants at G = 300 kg/m^{2}s, (b) Saturation temperature variation effect.

3. Data reduction

Pressure drop was noted along with a differential pressure sensor. The measured pressure drop has several contributions, as clarified in Eq. (1). Utilizing standard conventions (as discussed by Maqbool et al. [40]) $dp_{end\ effect}$ and dp_{sp} were estimated from well-established correlations. The dp_{tp} was then determined from measured pressure drop and estimated single-phase and end effects pressure drop effects (see Eq. (1)). Two-phase pressure drops have additional contributions from accelerational, gravitational and frictional effects (Eq. (2)).

$$dp_{measured} = dp_{end\ \ effect} + dp_{tp} + dp_{sp} \tag{1}$$

$$dp_{tp} = dp_{accelerational} + dp_{gravitational} + dp_{frictional} \tag{2}$$

Gravitational pressure drop is due to the orientation of the test object and was calculated by using Eq. (3).

$$\left(\frac{dp}{dz}\right)_{gravitational} = g\sin\varnothing\left(\alpha\rho_g + (1-\alpha)\rho_l\right) \tag{3}$$

According to the homogenous model, α is the void fraction, two pahse viscosity defintions used with homogenous models are summarized in Table 3.

$$\alpha = \left[1 + \left(\frac{\rho_g}{\rho_l}\right)^{\frac{2}{3}}\left(\frac{1-x}{x}\right)\right]^{-1} \tag{4}$$

Liquid and vapor-phase's momentum discrepancy were consequential during the evaporation procedure that causes an acceleration pressure drop.

$$\left(\frac{dp}{dz}\right)_{accelerational} = \left[\frac{\upsilon_l(1-x)^2}{1-\alpha} + \frac{\alpha\upsilon_g}{x^2}\right]G^2 \tag{5}$$

4. Results and discussion

4.1. Effect of mass flux and vapor quality

Experimental findings for two-phase frictional pressure drop for four tested refrigerants at $T_s = 32$ °C for various mass velocities are shown in Fig. 3. Consequently, frictional pressure drop increment with mass flux and vapor quality at exit of the test piece were noticed. A peak was observed somewhere at 85% vapor quality at the test specimen exit in all cases. This indicates incipience of dry out. Similar qualitative trends were noticed with results collected at 27 °C.

The qualitative findings from current study are in agreement with [40–43].

Table 4
Outline of important statistical data about the tested correlations.

Correlation	MAE	Percentage of data within ±30%
Consolini and Thome [47]	27.08	54.12
Ramirez-Rivera et al. [54]	23.45	29.20
Cavallini et al. [50]	27.24	71.78
Sun and Mishima [55]	39.44	33.02
Yang and Web [56]	46.78	29.04
Yu et al. [52]	42.19	26.63
Mishima [57]	24.04	30.95
Wang et al. [48]	34.36	53.55
MüllerSteinhagen and Heck [51]	40.71	27.55
Tran et al. [58]	45.23	47.62
Lockhart & Martinelli [49]	52.36	42.49
Hwang and Kim [59]	55.67	39.63
Friedel [31]	34.59	37.47
Li and Wu [60]	41.74	37.01
Jung & Radermacher [61]	33.33	46.41
Grönnerud [62]	30.77	52.05

4.2. Effect of saturation temperature

The obtained consequences of pressure drop for four refrigerants under similar operating conditions are shown in Fig. 4a, whereas saturation temperature variations are demonstrated in Fig. 4b. R1234yf exhibited the lowest pressure drop, whereas R152a showed the highest pressure drop employing a similar operating scenario. Thermophysical properties mainly control flow characteristics of any fluid, high thermal conductivity, low surface tension and viscosity are generaly considered to be favorable from hydrothermal aspects. Frictional pressure drop was noticed to decrease with increment in saturation temperature, reduced surface tension and viscosity at high operating temperature might be the reason behind this observed phenomenon. The qualitative trends are in agreement with [44–46].

4.3. Comparison with correlation

The findings have been analyzed via comparison with literature correlations. For this purpose, the test object was considered to be composed of ten equally spaced parts, the pressure gradients were calculated for these subparts, and the overall pressure drop was finally estimated by summation of all forstated pressure drops. For this assessment, two mathematical parameters MAE and percentage of data within ±30%, have been utilized. MAE shows the comparison of predicted values and the experimental results $\left[\mathrm{MAE} = \frac{1}{N}\sum_{1}^{N}\left(\frac{x_{predicted} - x_{experimental}}{x_{experimental}}\right)*100\right]$. The detailed summary is provided in Table 4, and the graphically trends are shown in Fig. 5.

Consolini and Thome [47] proposed a correlation to predict two-phase frictional pressure drop (see Fig. 5). This was created via a large databank (6291 data points) collected with 13 fluids and tubes with 3–25 mm diameter (see Fig. 5). The author used the drift-flux model in which relative motion was discussed rather than the individual motion of fluid particles. Comparatively, good predictions have been demonstrated by our data for R134a where over predictions were noticed with R600a and R1234yf and under predictions were noticed with R152a.

The correlation from Wang et al. [48] was also tested from its prediction capability. This correlation is based on Lockhart and Martinelli [49] approach. Wang et al. [47] did experiments with different refrigerants with a 6.5 mm horizontal tube. A comparison of this correlation demonstrates robust predictions for R152a, the modified multiplier is independent of mass flux.

For condensation, the pressure drop in tubes with 0.2–3 mm diameter has been reported by Cavallini et al. [50]. Comparison of data reported in this paper shows scattered predictions with R152a, whereas data was mostly over predicted for other tested mediums.

MüllerSteinhagen and Heck [51] studied and proposed pressure drop prediction correlation in conventional channels. The correlation is based on a databank collected with fourteen refrigerants under broad operating conditions. Our data demonstrate over predictions for R134a, R1234yf and R600a.

Friedel [31] proposed a pressure drop quantification correlation in an upward flow situation. The experiments were conducted with channel diameters from 0.98 to 257.4 mm and operating pressure in the range of 0.06–21 MPa. The experimental databank approximately contained 16,000 data points with 13 fluids (R11, R22, R113, water-steam, water-air, oil-air, water-methane, oil-methane, water-nitrogen, alcohol-argon and water-argon). Experiments were conducted for both circular and non-circular conduits. Comparison between our data and the correlation as mentioned above shows under predictions of data for all tested mediums as shown in Fig. 5.

Two-phase pressure drop was reported by Yu et al. [52] in a horizontal tube with a 2.9 mm diameter. Tests were conducted at 200 kPa system pressure and for 0.9 m heated length. Experimental findings as well as comparison with correlations, were reported. A modified form of Chisholm correlation [53] was proposed to predict the pressure drop in small channels. Comparatively, this

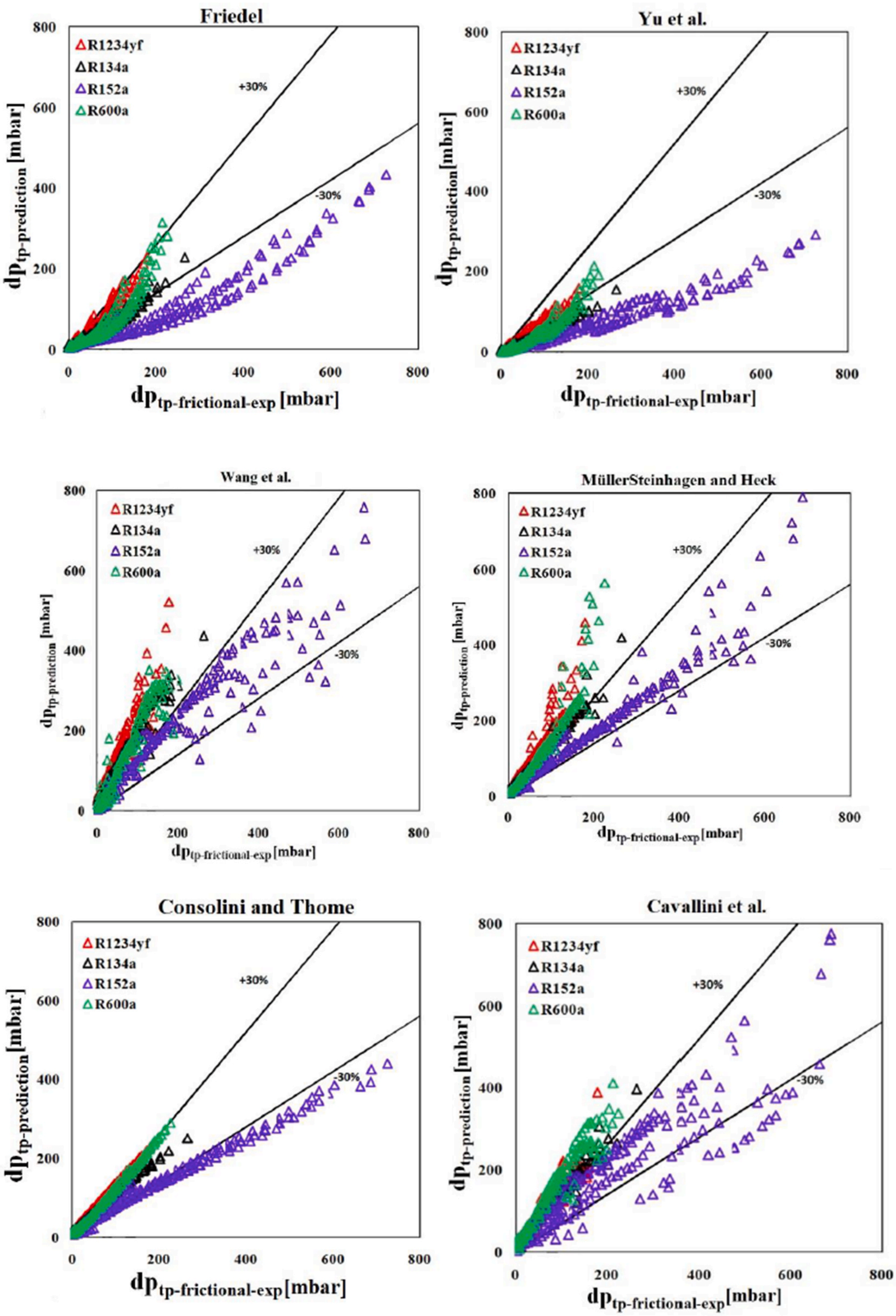

Fig. 5. Comparison of six correlation (a) Friedel correlation [31] (b) Yu et al. [52] correlation (c) Wang et al. [48] correlation (d) Müller Steinhagen and Heck [51] correlation (e) Consolini and Thome [47] correlation (f) Cavallini et al. [50] correlation.

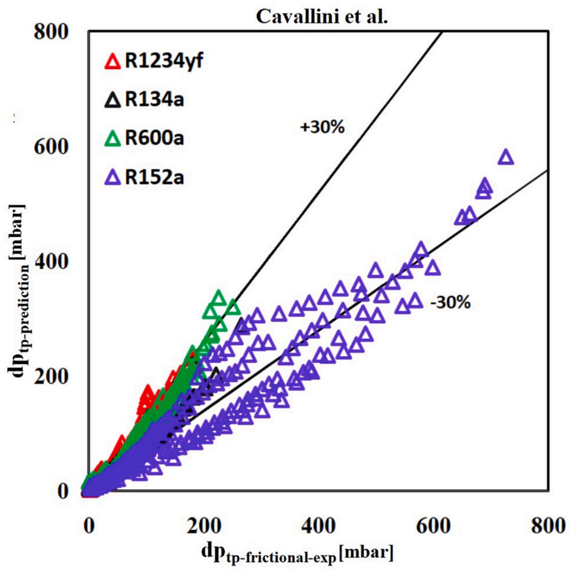

Fig. 6. Newly proposed correlation.

correlation under predicts according to our findings for two-phase frictional pressure drop.

Table 4 gives an overall summary of the prediction of assessment methods. Two statistical parameters MAE and percentage of predicted data within ±30% of the brand error, have been utilized for this assessment exercise. All well-known correlations have been tested for their predictions against the current database.

4.4. New proposed correlation

This section presents new correlation development for frictional pressure drop assessment during boiling in mini/microchannels. The annular flow region is a crucial constituent regarding pressure drop characteristics. The entrained liquid fraction can be explained as the liquid flow fraction in droplets in the gaseous phase. Therefore, it increases the density of the vapor phase that causes a reduction in pressure. The new correlation (Eq. (6)) was developed using regression analysis and is a revised version of Cavallini et al. [38]. The newly proposed correlation has predicted 71.78 % of data (Fig. 6) within ±30% brand error.

$$F = \frac{x^{0.9525} * (1 - x)^{0.414}}{3.25} \tag{6}$$

5. Conclusion

Experimental findings on two-phase frictional pressure drop regarding four refrigerants (R1234yf, R152a, R600a and R134a) have been discussed. The main observations were;

- Mass flux, vapor quality and system operaitng pressure were noticed to be the key parameters affecging frictional pressure drop.
- Among tested mediums, R1234yf showed a slightly lower pressure drop than R134a, whereas R152a and R600a showed a significantly higher pressure drop. The difference could be explained by the difference in the thermophysical properties of these mediums.
- The frictional pressure drop decreased with saturation temperature, reduced surface tension and viscosity are possibly be the reason for this observation.
- Twenty existing prediction models have been tested, and a modified correlation for the prediction of two-phase frictional pressure drop has been proposed. New correlation predicted over 70% of data within ±30%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The data that supports the findings of this study are available within the article.

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