Pressure drop during condensation at low mass fluxes in smooth horizontal and inclined tubes

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ABSTRACT

There are limited studies on pressure drops at low mass fluxes in smooth horizontal and inclined tubes. Thus, this paper presents the pressure drops during the condensation of R134a at low mass fluxes in smooth horizontal and inclined tubes with an internal diameter of 8.38 mm. Experiments were conducted at a saturation temperature of 40 °C at mass fluxes of 50, 75 and 100 kg/m^{2}s, and mean vapour qualities between 0.1 and 0.9. The temperature differences (between the mean saturation temperature and mean wall temperature) tested were 1, 3, 5, 8, and 10 °C. The pressure drops between the test section inlet and outlet over a length of 1.71 m were measured and were found to be temperature difference dependent. The flow patterns were captured concurrently with two high-speed video cameras positioned at the entrance and exit of the test section through sight glasses. The effect of the vapour quality, temperature difference, mass flux, and inclination angle on the measured and frictional pressure drop was analysed and discussed. It was found that the pressure drops increased with an increase in mass flux, temperature difference and vapour quality. Furthermore, the lowest and highest measured pressure drops were obtained during the downward and upward flows respectively. On the other hand, the opposite was found for the frictional pressure drops.

Keywords: inclination, frictional, pressure drop, condensation, temperature difference

Highlights

- Experimental pressure drops at low mass fluxes during condensation
- Pressure drops at different inclination angles and temperature differences
- Pressure drops increased as temperature and inclination angles increased
- Frictional pressure drops are maximum during downward flows
- Frictional pressure drops increased with mass flux

NOMENCLATURE

d	diameter (m)
EB	energy balance (%)
g	gravitational acceleration
G	mass flux
$L_{\Delta P}$	distance between pressure taps
P	pressure
T	temperature
x	vapour quality
Greek symbols	
β	inclination angle
ε	void fraction
ρ	density
σ	surface tension
Subscripts	
fric	frictional
i	inner
in	inlet
l	liquid
line	lines between pressure taps and transducer
m	mean
meas	measurement
mom	momentum
out	outlet
rh	Rouhani and Axelsson
sat	saturation
stat	static
tp	two-phase
v	vapour
w	wall

1. Introduction

With soaring energy costs and the grave concerns about the environmental impact of some working fluids, efforts are now being stepped up more than ever before to ensure the proper design and optimisation of condensers used in refrigeration and air-conditioning systems, desalination plants and power generation plants [1-48]. Pressure drop is particularly crucial in forced convective systems because it is synonymous with pumping or compressor power consumption. In natural (free) convective systems, pressure drop determines the circulation rate; in nuclear power plants, high-pressure steam and water flow as a two-phase mixture within the piping networks and pressure vessels of different sizes and orientations. It is therefore imperative in this case, to predict the pressure drop and void fraction in the heat transport loop of nuclear reactors for safety and design analyses [10, 13, 24, 49]. In general, the pressure drop is intimately linked to the quantity of energy needed to move flow through a two-phase system and is a fundamental parameter in two-phase flow design and modelling.

There have been various experimental studies on pressure drops during condensation inside smooth horizontal tubes [5-7, 10, 12, 13, 17, 18, 20, 24, 27, 28, 35, 37, 40, 46, 50-62]. Most of these studies were conducted at mass fluxes equal to or greater than 200 kg/m^2s and typically reaching up to 1 000 kg/m^2s. In these studies, it was found that an increase in vapour quality and mass velocity led to an increase in the pressure drop. It was also found that higher pressure drops were recorded at lower saturation temperatures and that low-pressure fluids gave higher pressure drop. There have also been quantitative studies [3, 19, 26, 63-67] aimed at comparing pressure drop models with the results of empirical studies. Furthermore, various two-phase pressure drop predictive models [14, 16, 21, 22, 25, 41, 64, 68-88] have been developed. The challenge is that these models are at variance with one another. Also, of all the models developed, those of Moreno *et al.* [21] (developed for evaporation), Chen *et al.* [89], Garimella [41], Cavallini *et al.* [77], Quiben *et al.* [21] and Xiao and Hrnjak [90] were the most prominent derived as a function of the prevailing flow pattern. Other models have either been empirical or analytical and are limited to particular working fluids, tube size, heat fluxes, and mass flow rates. This implies that they are not expected to be very accurate. On the other hand, general frictional pressure drop correlations have been formulated based on either separated or homogeneous flow. However, the separated models are mostly used for two-phase flows.

A review of the general literature on pressure drop inside smooth tubes is highlighted below and presented in two sections. Sec. 1.1 is dedicated to horizontal tubes while Sec. 1.2 is assigned to inclined tubes.

1.1. Pressure drop in horizontal tubes

Ferguson and Spedding [57] conducted experimental and comparative studies on pressure drop during two-phase co-current air-water flow in a horizontal Perspex pipe with an internal diameter of 9.35 mm and a length of 12.8 m. The results of their experiments were used to test the prediction of pressure drop in a variety of models. They found that particularly with the stratified flow regimes, the model suggested by Olujic [91] was the most accurate. They also recommended different models for other flow regimes found in their study and explained why predictions in other specified flow regimes were unsuccessful.

Cavallini *et al.* [11] investigated heat transfer coefficient and pressure drop during the condensation of refrigerants R134a, R125, R32, R410A, and R236a within a vapour quality range between 0.15 to 0.85. Their saturation temperature range was between 30 and 50 °C. They found that pressure drop increased with mass flux and vapour quality and that the pressure drop was highest at the lowest saturation temperature (30 ºC). They also found that lower pressure fluids resulted in higher pressure drop. The Rohuani [92, 93] void fraction model was used in estimating the momentum pressure drop. They chose this model because of the small change in vapour quality across the test section which implied that the momentum pressure drop was expected to be negligible. Finally, they concluded that pressure drop behaviour was crucial in ascertaining the overall thermal performance of different fluids.

Son and Oh [23] investigated pressure drop during the condensation of R22, R134a, and R410a at mass fluxes between 450–1 050 kg/m^{2}s inside a circular microtube, 3.38 mm in outer diameter, at a saturation temperature of 40°C. It was found that the condensation pressure drops for R22, and R410A were lower than that of R134a for the same mass fluxes. They also found that the pressure gradient decreased as the vapour quality decreased. Furthermore, their experimental results were compared with 14 two-phase flow pressure drop models, and it was found that the Chen *et al.* [13] correlation gave the lowest overall deviation for the three refrigerants. They attributed this to the fact that their tube diameter size and mass fluxes were in the same range as that used by Chen *et al*. [13] even though there was a difference in the range of saturation temperatures. After that, they leveraged on the results of their experiments and the Lockhart-Martinelli [68] two-phase multiplier method to develop a new correlation which predicted the results of their tests satisfactorily.

Bohdal *et al*. [10] presented the results of their experiments during the condensation of R134a, R407C, and R404A in mini-channels with their maximum tube being 3.3 mm in diameter. They found a significant dependence on pressure drop on the refrigerant type, process parameters, and structure of the two-phase flow. It was also found that an increase in the mass flux led to an increment of the flow resistances in local conditions. They proposed a correlation for determining the frictional pressure drop in the annular, annular wavy, and stratified two-phase flow regimes covering a temperature range between 20 and 50 °C, vapour qualities between 0 and 1, and mass fluxes between 0 and 1 300 kg/m^{2}s.

Goss *et al.* [39] investigated pressure losses during the convective condensation of R134a in horizontal and parallel circular microchannels. Their test conditions were saturation temperatures between 28 to 40 °C, qualities from 0.5 to 1, heat fluxes from 17 to 53 kW/m^2, and mass fluxes from 230 to 445 kg/m^{2}s. They quantified the contributions of fluid acceleration, contraction, expansion, flow direction changes and friction to the total pressure drop; they found that the frictional pressure drop component corresponded to 95% of the total pressure loss. They also investigated the influence of condensation temperature, heat flux, and mass velocity on the pressure drop and found that the pressure drops decreased with a decrease in mass flux but increased with a reduction in saturation temperature. They also found that the pressure drops were not affected as much by the heat flux. Finally, they compared the results of their experiments with various correlations and semi-empirical models and found that the model proposed by Cavallini *et al.* [94, 95] gave the best prediction performance.

Xu *et al.* [25] evaluated 29 frictional pressure drop models for two-phase flow in tubes by collecting 3 480 data points from previous experiments. The hydraulic diameters of the tubes considered ranged from 0.0695 mm to 14 mm, and mass fluxes ranged from 6 to 6 000 kg/m^{2}s. They compared these experimental data with these models and investigated the significance of the mass flux, vapour quality, tube diameter and working fluid on the frictional pressure drop. They concluded that the correlations of Muller-Steinhagen and Heck [22], and Sun and Mishima [70] predicted the entire range of the experimental data under different conditions with the best accuracy and recommended them for use in the design of two-phase flow systems.

Dalkilic *et al.* [3] presented a comparative analysis of the results of their experiments against eleven different pressure drop models during the annular flow condensation of R600a in a horizontal tube and R134a in a vertical tube at condensation temperatures between 30 °C and 50 °C. Their test mass fluxes were between 75 and 400 kg/m^{2}s. The diameter of their vertical tube was 8 mm, while the diameter of the horizontal tube was 4 mm. They used the Chisolm void fraction model [14] to calculate their momentum pressure drops. They asserted that compared to other correlations, that of Chen *et al.* [13] gave the best prediction in comparison with the results of their experiments. However, they found a considerable variation in the capability of the different models to correctly predict the results of their experiments.

Wang *et al*. [24] performed a theoretical study of friction pressure drops during laminar flow condensation in microchannels and reported a fair agreement at high vapour qualities and lower results when compared to some correlations at lower vapour qualities.

Wang *et al*. [37] conducted experiments to measure the frictional pressure drop during the condensation of steam in a horizontal vacuum tube. They varied the steam saturation temperature from 50 to 70 °C using mass fluxes from 2 to 10 kg/m^2s across the whole vapour quality range. They maintained the temperature difference between the cooling water at 3, 5, and 8 °C. It was found that all their test points corresponded to the stratified flow regime. They also found that frictional pressure drop increased with mass flux and vapour quality but decreased with saturation temperature. Furthermore, they found that the frictional pressure drop did not depend much on the temperature difference. They compared the results of their experimental data with 25 existing frictional pressure drop models. It was found that the Quibén's model [21], Chisholm's model [14], Zhang's model [74], Sun's model [45, 70], Lee's model [73] had the best prediction accuracy.

Yan and Lin [35] investigated heat transfer and pressure drop during the condensation of R134a inside a horizontal circular pipe with an internal diameter of 2 mm. Their test conditions were mass fluxes of 100-300 kg/m^2s, and saturation temperatures between 25 and 50 °C. They investigated the effects of the mass and heat flux, vapour quality and saturation temperature on the measured pressure drops and heat transfer. They found that the pressure drop increased with mass flux. They also found that the pressure drops were lower at higher saturated temperatures. Based on their experimental data, they developed empirical correlations for friction factors.

Zhuang *et al.* [96] studied the thermal performance of R170 (ethane) undergoing condensation at saturation pressures that ranged from 1 MPa to 2.5 MPa, in a horizontal tube with an internal diameter of 4 mm. Their test mass fluxes were from 100 kg/m^2s to 250 kg/m^2s, and heat fluxes were from 55.3 kW/m^2 to 96.3 kW/m^2 over the complete range of vapour qualities. They examined the effects of vapour quality, mass flux and saturation pressure on condensation heat transfer and pressure drop. It was found that frictional pressure drop increased with mass flux. As saturation temperature was increased, the effect of mass flux weakened. They also found that frictional pressure drop decreased as the saturation pressure increased. However, at the lowest mass flux of 100 kg/m^2s, both the saturation pressure and vapour quality had little influence on the frictional pressure gradients. In conclusion, it was found that the Yan and Lin correlation [35] predicted the experimental pressure drop with a mean absolute deviation of less than 18%.

1.2. Pressure drop in inclined tubes

Wongwises and Pipathattakul [97] studied pressure drops, flow patterns, and void fractions during horizontal and upward inclined air-water two-phase flow in a concentric annular test section with a length of 880 mm and an outer diameter of 12.5 mm. They found that their experimental test conditions corresponded to plug, slug, annular, annular/slug, bubbly/plug, bubbly/slug–plug, churn, dispersed bubbly, and slug/bubbly flows. At low gas and liquid velocities, it was found that the pressure drops increased when the inclination angle changed from horizontal to 30º and 60º. At the same time, the void fractions increased with increasing gas velocity. They also found that the opposite was true for increasing liquid velocity.

Maddi and Rao [98] performed experiments during flow boiling of water in inclined tubes encountered in the design of solar collectors, The angle of inclination was varied from 0° to 90°. It was found that inclination had a significant influence on the transport process, particularly in the bubbly and the intermittent flow regimes. However, they found that inclination had only a marginal effect on the annular flow regime. The Baroczy [99] and the Lockhart-Martinelli [68] correlations were then used to evaluate the frictional pressure drop in the flow process.

Bhagwat and Ghajar [38] studied pressure drops, void fractions, flow patterns, and heat transfer coefficients for non-boiling air-water two-phase flow in the entire range of downward inclinations. Their test section was a tube with an inner diameter of 12.5 mm. Their measurements were taken over a vast range of liquid and gas phase mass fluxes to cater for the prevalent flow regimes experienced during downward inclined gas-liquid flow. It was found that there was an effect of the tilting on two-phase flow patterns, especially at low mass flow rates. A significant impact of pipe inclination was also seen on the transition between stratified and non-stratified (slug, intermittent) flow patterns. They concluded that the two-phase flow parameters such as void fraction, pressure drop and heat transfer coefficient were mainly influenced by the negative slippage at the gas-liquid interface controlled by the buoyancy-driven nature of the two-phase flow. Furthermore, they also found the two-phase flow parameters were not sensitive to the variation in downward pipe inclination in the inertia driven region of the flow patterns.

Autee *et al.* [100] performed an experimental study of pressure drops during the two-phase flow of air-water mixtures in transparent acrylic tubes with diameters of 4.0, 6.0, and 8.0 mm with a length of 400 mm orientated horizontally, vertically and at downward inclinations of 30° and 60°. The pressure drops were measured and compared with the six existing correlations frequently used in calculating the pressure drops in macro and mini-microchannels. It was found that the current models were inadequate in predicting the two-phase pressure drop for the three diameter sizes. Based on the results of their experiments, they proposed a new correlation for predicting pressure drops by modifying the Chisholm parameter [14] and integrating different parameters. It was found that the proposed correlation predicted two-phase pressure drops satisfactorily.

Lips and Meyer [7, 18] investigated pressure drops during the condensation of R134a in a smooth horizontal and inclined tubes at a saturation temperature of 40°C and constant heat transfer rate of 200 W. For vertical upward flows; they found that the results of their experiments agreed with various pressure drop correlations. It was found that no model predicted their measurements correctly for downward flows. They defined an apparent gravitational pressure drop and a void fraction to study the inclination effect on the two-phase flow. For upward flows, they found that the void fraction and the frictional pressure drop did not depend on the inclination angle, but this was not the same for downward flows. In conclusion, they compared the results of their experiments with the model of Taitel and Dukler [101] for the stratified downward flow regime, and an excellent agreement was found.

Adelaja *et al.* [9] conducted experiments to determine the pressure drops during the condensation of R134a in an inclined smooth inclined tube with an inner diameter of 8.38 mm across a wide range of vapour qualities. The mass fluxes tested were between 100 kg/m^{2}s and 400 kg/m^{2}s at saturation temperatures from 30 - 50°C. They computed their momentum pressure drop with the void fraction model of Bhagwat and Ghajar [102]. They found that the highest void fractions and pressure drops were for vertical downward flows. Furthermore, that the pressure drops and void fractions increased with decreasing saturation temperatures. The opposite was true when the inclination angle was decreased. Furthermore, that the maximum frictional pressure drops were for downward flow, while the lowest values were found for upward and horizontal flows.

Kang *et al.* [31] studied the effect of inclination angles on pressure drops during the condensation of steam in a flattened tube with a length of 10.7 m and a very low mass flux of 6.8 kg/m^{2}s, as is typically found in air-cooled steam condensers in the power generation industry. The steam was superheated at the inlet, and the inclination angles varied from horizontal (0°) to 70°. A uniform velocity profile of 2.03 m/s was imposed on the air side to remove heat from the steam. Initial two-phase pressure drop measurements and flow visualizations showed a reduction of pressure drops due to enhancement in the gravity-assisted drainage of condensate inside the tube, although the growth was only seen at an early stage of inclination.

Most recently Noori Rahim Abadi *et al.* [103] performed a comprehensive numerical study that investigated the pressure drops during the condensation of R134a inside a smooth tube at different inclination angles. The tube had an internal diameter of 8.38 mm and a length of 1.488 m while the saturation temperature was maintained at 40 °C. Simulations were carried out throughout the possible angles of inclination from -90° to +90°. The heat flux was kept constant at approximately 5 kW/m^2 while the mass fluxes were varied from 100-600 kg/m^2 s. The volume of fluid (VOF) multiphase flow formulation coupled with the ANSYS FLUENT™ CFD program was utilized to solve the fundamental governing equations. The simulated results showed good agreement with the results of the experiments of Adelaja *et al.* [8, 9], and in general, they found that the inclination effects on the void fractions and pressure drops were negligible at high mass fluxes and vapour qualities. Furthermore, they found that the measured pressure drops increased as the void fractions, and mass fluxes increased. These increments were found to be more noticeable at high vapour qualities.

1.3. Problem statement and purpose of the study

It can be concluded from the literature that there is a gap in the open literature on pressure drops during condensation in smooth (Sec 1.1) and inclined tubes (Sec 1.2) at specifically low mass fluxes where the pressure drops are temperature difference dependent. To the best of our knowledge, there has been no study on the effect of temperature differences (defined in this study as the temperature difference between the saturation temperature and the wall temperature) on pressure drop at low mass fluxes. When evaluating correlations, it was found they did not agree with another. While the Friedel [16] correlation seems to be the most cited, it was developed for high reduced pressures and high mass fluxes. On the other hand, the correlations of Muller-Steinhagen and Heck [22], Sun and Mishima [70], Chen *et al.* [13], and Grönnerud [69] usually gave the best predictions when compared with various experimental results (at high mass fluxes). It implies that further research needs to be carried out to develop more pressure drop correlations.

It was therefore the purpose of this study to present new experimental data for pressure drops during the condensation of R134a in a horizontal and inclined tube at a saturation temperature of 40 ºC at low mass fluxes and different temperature differences. It is a continuation of the authors' previous works [104-106] in which the heat transfer coefficients and flow regimes during condensation in smooth and inclined tubes were studied. Pressure drops were not presented in these studies.

2. Experimental facility

The test bench (Fig. 1) used for the present study is an established facility that has been used previously in several research projects on in tube condensation [7-9, 18, 32, 33, 105, 107-112] and is therefore not described in this study. The relevant test bench modifications required for the low mass fluxes of this study have been explained in [104-106].

The extra information not previously given is that the pressure of the refrigerant entering and exiting the test section was measured with strain gauge pressure transducers with an error of ±2 kPa. These values were correlated with the corresponding saturation temperature on the condensation saturation curve given in REFPROP [113]. The variation in the two values was found to be less than 0.1°C at high mass fluxes (300 kg/m^{2}s and above) and high vapour qualities while a higher difference was observed at mass fluxes lower than 200 kg/m^{2}s and low vapour qualities. This, however, might be caused by the nature of the prevailing flow pattern at low mass fluxes.

Two calibrated differential pressure transducers with diaphragm capacities of 0.86 kPa and 14 kPa connected in parallel between the entrance and the exit of the test condenser over a length of 1.71 m were used to measure the pressure drops. The sizes of the diaphragms were carefully chosen and were calibrated to an error of ±0.05 kPa. The distance between the two pressure taps was $L_{\Delta P}$ = 1 710 mm ± 2 mm. Electrical heating wires were wrapped around the pressure tap lines and heated to approximately 5 °C above the condensation temperature to prevent condensation in the lines. This was similar to what was done by Cavallini *et al.* [114], Lips and Meyer [7, 18, 107, 108] and Adelaja *et al.* [8, 9, 33, 109].

3. Data reduction

The pressure drops were determined as was done by Adelaja *et al*. [8]. The frictional pressure drops were calculated as:

$$\Delta P_{fric} = \Delta P_{meas} + \Delta P_{line} - \Delta P_{mom} - \Delta P_{stat} \tag{1}$$

The measured pressure drops, ΔP_{meas}, were obtained from the transducer pressure drop measurements. ΔP_{line} was the measured line pressure drop difference due to the height difference as a result of varying the angles of inclination. The line pressure drop is important because it measures the static pressure difference effect due to the vapour that was trapped in the pressure lines. It was calculated as:

$$\Delta P_{line} = \rho_v g L_{\Delta P} \sin\beta \tag{2}$$

where, ρ_v was the refrigerant vapour density obtained from the measured saturation temperature and REFPROP [113]. The gravitational acceleration was taken as 9.81 m/s^2. $L_{\Delta P}$, was the measured distance (1.71 m) between the two pressure taps and, β, was the measured inclination angle of the test section. The inclination angle was taken from the horizontal. The inclination angle was considered as positive for upward inclinations, zero for horizontal inclinations, and negative for downward inclinations. For horizontal flow (β = 0º) which implies that $\sin\beta = 0^{\circ}$, which means that $\Delta P_{line} = 0$.

The static pressure drops, ΔP_{stat}, caused by the difference in height from one side to the other side in the test section were dependent on inclination angle and were calculated as:

$$\Delta P_{stat} = \rho_{tp} g L_{\Delta P} \sin\beta \tag{3}$$

From Eq. 3, it can be deduced the static pressure drop reduces to zero for horizontal flow (β=0º) scenarios. In the equation, ρ_{tp} represents the two-phase density and was determined as recommended by [115-119]. This expression represents a homogenous model and was calculated as:

$$\rho_{tp} = \rho_l(1-\varepsilon) + \rho_v\varepsilon \tag{4}$$

From Eqs. 4 and 5, the surface tension, σ, the liquid phase density, ρ_l, and the vapour phase density, ρ_v, were all determined at the measured condensation temperature (which was cross checked against the measured saturation pressure) with REFPROP [113]. The void fraction, ε, for horizontal and inclined flows respectively, were calculated using the Steiner versions of the drift-flux model of the Rouhani and Axelsson model [92, 93] as:

$$\varepsilon_{rh} = \frac{x}{\rho_v}\left[1 + 0.12(1-x))\left(\frac{x}{\rho_v} + \frac{1-x}{\rho_l}\right) + \frac{1.18(1-x)\left(g\sigma(\rho_l - \rho_v)\right)^{0.25}}{G^2\rho_l^{0.5}}\right]^{-1} \tag{5}$$

$$\varepsilon_{rh} = \frac{x}{\rho_v}\left[[1 + 0.2(1-x))\left(\frac{gd\rho_l^2}{G^2}\right)^{0.25}]\left(\frac{x}{\rho_v} + \frac{1-x}{\rho_l}\right) + \frac{1.18(1-x)\left(g\sigma(\rho_l - \rho_v)\right)^{0.25}}{G^2\rho_l^{0.5}}\right]^{-1} \tag{6}$$

It should be noted that Bhagwat and Ghajar [102] developed a flow pattern independent drift flux model based void fraction correlation for a wide range of gas-liquid two phase flows suitable for inclined tubes. However, when comparing their void fraction predictions with that of Rouhani and Axelsson, it was found that the average deviation was less than 3% which translated to a negligible deviation of about 1% in the calculated measured pressure drops. Hence, we opted to use the models listed in Eqs. (5 and 6).

Finally, the momentum pressure drop was calculated making use of the void fraction calculations as recommended by Carey [120] as:

$$\Delta P_{mom} = G^2 \left[\left(\frac{(1-x)^2}{\rho_l(1-\varepsilon)} + \frac{x^2}{\rho_g \varepsilon} \right)_{out} - \left(\frac{(1-x)^2}{\rho_l(1-\varepsilon)} + \frac{x^2}{\rho_g \varepsilon} \right)_{in} \right] \tag{7}$$

The mass flux, *G*, was calculated from the measured refrigerant mass flow rate and cross-sectional area of the test section. The vapour qualities were determined as described in our previous works [104-106]. Furthermore, the temperature differences (ΔT) referred to in this paper are the temperature differences between the average refrigerant saturation temperature, T_{sat}, and the average inner wall temperature, $\overline{T}_{w,i}$, as explained in refs. [104-106]. The operating conditions and average energy balances (as defined in refs [104, 106] for the experimental matrix is given in Table 1.

An uncertainty analysis was conducted as prescribed by Dunn [121] and the full details can also be found in Meyer and Ewim [106]. In this study, it was found that the maximum pressure drop uncertainty was 9%. A selection of approximately 60% of the experiments was repeated three months later to check possible drift in measurements, and the differences in results were compared. The maximum percentage differences of the measured pressure drops when the tests were repeated, was about 5%. This maximum difference was found at a vapour mass flux of 50 kg/m^{2}s, qualities below 0.25 and inclination angles of +90° and -90°.

4. Validation

A validation study was conducted to establish the integrity of our test rig and the results emanating from it. The validation experiments are summarised in Table 2 and identified 45 different conditions that were considered for experimental comparison purposes. The validation experiments were conducted at a saturation temperature of 40 ºC. The mass fluxes range of 200 - 400 kg/m^{2}s, at a mean vapour quality of 0.5 for inclination angles of -90° ≤ β ≤ +90° and with heat transfer rates of about 250 W. This was done to repeat the experimental conditions of Lips and Meyer [7, 18] and Adelaja *et al*. [8, 33]. The measurements compared well and were within the pressure drop uncertainties.

5. Results

The results of 900 pressure drop measurements with conditions as given in Table 3 are presented in three sections covering flow visualisation (5.1), measured pressure drops (5.2) and the frictional pressure drops (5.3).

5.1 Flow pattern visualisation results

The flow pattern results were extensively discussed in our previous papers [104-106] and will not be repeated in this paper. However, a brief description is presented in this section.

Fig. 2 summarizes the six flow patterns observed in this study. These flow patterns are smooth stratified (S), stratified wavy (SW) (also observed in Meyer and Ewim [106]), annular (A), annular wavy (AW), intermittent (I), and churns flows (C). These flow patterns were adopted using the descriptions of flow regimes prescribed by Thome [106, 122]. Bubbly flow was not observed on its own but was observed during intermittent flows. The flow pattern abbreviations S, SW, A, AW, I, and C are used to identify the flow patterns in Figs. 3 and 4. In these figures, the flow patterns are given for two different mass fluxes 100 kg/m^{2}s (Fig. 3) and 75 kg/m^{2}s (Fig. 4) as a function of inclination angles and temperature differences for mean qualities of 0.5 and 0.25, respectively. These were chosen to reflect the entirety of the flow patterns observed in this study.

5.2 Measured pressure drop

The measured pressure drops for mass fluxes of 100, 75, and 50 kg/m^{2}s are plotted as functions of the different inclination angles with varying temperature differences at various mean vapour qualities of 0.25, 0.5, and 0.75 as shown in Figs. 5 - 7. In general, the results showed the same trends of measured pressure drops as a function of mass flux, and vapour qualities that have been established in previous works. Thus, in general, the measured pressure drops increased with increasing values of vapour quality and mass flux. Other trends that have been experienced will be divided based on contributing parameters such as inclination angle, temperature differences, mass fluxes and vapour qualities.

5.2.1 Inclination angles

The inclination angle had a significant effect on the measured pressure drop (ΔP_{meas}) as shown in Figs. 5 - 7. The trend of variations in measured pressure drop may be attributed to the gravitational force which acts in the opposite direction when the tube is gradually tilted to the vertical upward directions. The maximum measured pressure drops were obtained during the upward flows (+60° $\leq \beta \leq$ +90°), while the minimums were found during the downward flows between (-90° $\leq \beta \leq$ -60°). The results wherein higher measured pressure drops were found during the upward inclination can further be explained by the fact that as the tube is inclined upwards, the mean flow velocity reduced which subsequently increased the liquid film thickness as can be deduced from the flow patterns in Figs 3 and 4. The results wherein lower measured values were found during the downward inclination was as a result of the reduction of pressure drop due to gravity-assisted drainage of condensate. Consistent with the findings in Ewim and Meyer [104], at an inclination angle (β) = -90° and vapour quality of 0.25, the outlet flow regime was churn which is characterised by the presence of Taylor bubbles within the core of the tube.

With an increase in the inclination angle to -30° ≤ β ≤ -15°, (Figs. 3 and 4), the vapour flowed at the top of the tube, while the liquid film remained at the bottom due to the effect of the gravity force and thus a stratified wavy flow regime. In this flow regime, there was direct contact between the vapour and tube wall, and as a result, there was an increase in the measured pressure drop. With an additional increase in the inclination angle, the liquid film thickness increased which further led to a rise in the measured pressure drop. We can also relate the increase in the measured drop as the inclination angle increased to a rise in the static pressure drop.

The upward flows generally led to a positive static pressure drop (ΔP_{stat}) and the opposite was true for downward flows. This is due to the fact that the sinus of the angle of inclination (β) was negative for downward flows but positive for upward flows. In essence, the static pressure drop was higher during upward flows, zero during horizontal flow and minimum during downward flows. To summarise, the variations of measured pressure drop with respect to the inclination angles may be ascribed to the variation of flow regime, the liquid film thickness on the tube surface, and the static pressure drop.

5.2.2 Temperature difference

The effect of the temperature difference on the measured pressure drops is shown in Figs. 5 - 7. It was found from our earlier work [104, 106] that during the smooth stratified and stratified wavy flow regimes which was typically characterised by low mass fluxes, an increment in the temperature difference (ΔT) led to a rise in the liquid film thickness. This increase in film thickness and consequent greater flow resistance best explains why there was an increase in the measured pressure drops as the temperature difference increased. This can be seen from Figs. 3 and 4 when comparing the flow patterns at a temperature difference of 10 °C and inclination angle of 0° to the flow pattern at a temperature difference of 3 °C at the same inclination angle. However, it seems as if the effect of temperature difference competed with the inclination effect on the measured pressure drops for this two-phase flow process. Also, at low mass fluxes, the low-velocity vapour flow and gravity forces caused downward flow of the condensate that formed at the bottom portion of the tube into the liquid pool during condensation. As the condensation occurred, the thickness of the film increased and this thick layer of liquid at the bottom of the tube increased with temperature difference leading to higher measure pressure drops.

5.2.3 Mass flux and vapour quality

In general, Figs. 5 - 7, show that there were an increase in the measured pressure drops with an increase in vapour qualities and mass fluxes. The increases in vapour qualities and mass fluxes increased the shear forces on the vapour–liquid interface causing a more unstable interface, thereby increasing the pressure drops. This can be deduced when comparing the flow pattern for a mass flux of 100 kg/m^{2}s (Fig. 3) and a mass flux of 75 kg/m^{2}s (Fig. 4). It can also be deduced that with a further increase of the vapour qualities and inclination angles, the shear forces caused the liquid film to be evenly distributed around the perimeter as the vapour travelled through the core of the tube. In general, since the effect of shear force began to manifest with increasing mass fluxes and quality, there were an expected increase in the measured pressure drops as mass fluxes, and vapour quality were increased.

5.3 Frictional pressure drops

The frictional pressure drops at mass fluxes of 100, 75, and 50 kg/m^{2}s are plotted as functions of different inclination angles with varying temperature differences at various mean vapour qualities of 0.25, 0.5, and 0.62 in Figs. 8 - 10. In general, the results showed some general trends of frictional pressure drop as a function of mass flux and vapour qualities that have been shown in previous work. Thus, in general, the frictional pressure drops increased with increasing values of vapour quality and mass flux. Other trends that have been found will be divided based on new contributing parameters such as inclination angles and temperature differences

5.3.1 Effects of inclination angles

From Figs. 8 - 10, it follows that the inclination angle had a significant effect on the frictional pressure drops. The trend of variations in frictional pressure drop may be attributed to the prevailing flow pattern and other parameters. The maximum frictional pressure drops were obtained during the downward flows, while the minimum was typically obtained during horizontal and vertical flows. The results wherein higher measured pressure drops were found during upward inclination angles is because the mean flow velocity reduced which subsequently caused higher static pressure drops and consequently, lower frictional pressure drops. This reduction in the flow velocity during upward flow weakened the wall-fluid, and the liquid-vapour shear stresses which produced a decrease in the frictional pressure drops.

Typically, at a mass flux of 100 and quality of 0.5, it was found that for downward flows, the flow pattern changed from mainly stratified-wavy at the near horizontal positions to annular at the vertical downward tube orientation. However, during the upward tube orientation, the flow pattern changes from stratified-wavy to churn at the vertical upward tube orientation. This variation of flow pattern with inclination angle was explicitly captured during the flow pattern analysis [104-106]. The change of frictional pressure drops with inclination angle can also be attributed to higher liquid holds during upward flows; hence predominant static pressure drops which adversely affected the frictional pressure drops. The opposite was true during downward flow where the liquid film decreased, resulting in a decrease in the wall-fluid, and vapour-liquid interfacial stresses hence an increase in the frictional pressure drop. To summarise, the inclination angle affected the flow patterns, and this manifested the frictional pressure drops.

5.3.2 Effect of temperature differences

The effect of the temperature difference on the frictional pressure drops is also shown in Figs. 8 - 10. In general, it was found that the frictional pressure drops increased with increasing values of the temperature differences for all angles of inclination. It has been shown from our previous works that as the liquid film thickness increased, the temperature difference increased, causing more resistance which leads to an increase in the frictional pressure drops. This can be seen from Figs. 3 and 4 when comparing the flow patterns at a temperature difference of 10 °C and inclination angle of 15° to the flow pattern at a temperature difference of 3 °C at the same inclination angle. The interaction between the fluid and the tube wall is intimately linked to the frictional pressure drop. The frictional pressure drops were found to be related to properties of the liquid film which was affected by the temperature differences. With an increase in temperature differences, the densities of the liquid film increased so increasing the wall-fluid, and vapour-liquid interfacial shear forces leading to an increase in the frictional pressure drops.

5.3.3 Effect of vapour qualities

From Figs. 8 – 10, it followed that the qualities and mass fluxes affected the frictional pressure drops. For the horizontal flows, there was an increase in the frictional pressure drops as the vapour quality was increased. However, for upward flows, the effect of inclination led to higher frictional pressure drops for lower vapour qualities ($x_m = 0.25$). The converse was true for downward flows. Furthermore, it was found that the frictional pressure drops were higher for upward flows and horizontal flows but lower for downward flows as the vapour qualities increased. At high vapour qualities ($x_m = 0.5$ and above), the frictional pressure drops increased with vapour quality for all orientations. This may be attributed to the fact that the same pattern was prevalent at those high vapour qualities. To summarise, the frictional pressure drops increased with an increase in vapour quality at 0.25 (Fig. 8a). However, as the vapour quality was increased (Fig. 8b) and (Fig. 8c), the frictional drop decreased with decreasing vapour qualities (for all downward flows) until a horizontal inclination angle when it began to rise again. Similarly, increasing qualities resulted in increasing vapour phase velocities and decreasing liquid phase velocities, which increased the slip between the two phases and resulted in increased frictional pressure drops.

5.3.4 Effect of mass fluxes

In general, it can be deduced from Figs 8 - 10, that the frictional pressure drops increased with mass fluxes for all vapour qualities and inclination angles. This can be attributed to the fact that the mass flux is closely linked with the fluid friction against the wall of the test section. Furthermore, since the interfacial shear stress on the tube depends on the mass fluxes and vapour velocities, the frictional pressure drops were affected by the increase in mass fluxes. Furthermore, an increase in mass flux resulted in an increase in the vapour and liquid velocities of the fluid. This increase caused higher wall shear stresses resulting in greater frictional pressure drops. This can be deduced when comparing the flow patterns for a mass flux of 100 kg/m^{2}s (Fig. 3) and a mass flux of 75 kg/m^{2}s (Fig. 4). Also, at low mass fluxes, the liquid films were typically asymmetric similar to stratified flow. However, increasing the mass fluxes led to a highly disturbed interface. In such conditions, the friction factor ratios appeared to be mainly a function of the liquid Reynolds number which also depended on mass fluxes. Hence, an increment in the mass flux will lead to an intensification of the turbulence of the flow consequently affecting the frictional pressure drop.

6. Conclusions

Limited studies have been conducted during the condensation at low mass fluxes where the pressure drops are a function of temperature differences. Therefore, pressure drop experiments were conducted during the convective condensation of R134a in a smooth horizontal and inclined tube at mass fluxes of 50, 75, and 100 kg/m^{2}s. The mean vapour qualities were varied from 0.1 to 0.9 at temperature differences of 1, 3, 5, 8, and 10 °C. In total, 945 experimental data points were collected for both the validation and low mass flux results. The flow regimes were captured using two high-speed cameras installed at the entrance and exit of the test condenser. The effects of mass fluxes, inclination angles, temperature differences, vapour qualities and mass fluxes were investigated on the measured and frictional pressure drops and were found to be significant. In all cases, the maximum measured pressure drops were found at the maximum temperature differences and inclinations angles between +60° and 90° (vertically upward). On the other hand, the maximum frictional pressure drops were found at the maximum temperature differences tested per data point and at an inclinations angle of -90° (vertical downward flow cases). Furthermore, the minimum measured pressure drops were always found at the lowest temperature differences tested per data point and at an inclination angle of −90° (vertically downwards flow). The frictional pressure drops were found to decrease with a decrease in temperature differences. Also, for horizontal and upward flows, the frictional pressure drops increased with an increase in vapour quality. However, for downward flows, it was higher at a vapour quality of 0.25 (low vapour qualities). On the contrary, at high vapour qualities (x_m = 0.5 and above), no significant additional impact of vapour quality was found on the inclination effect. It was found that increasing the mass fluxes and vapour qualities, led to a rise in both frictional and measured pressure drops, and this can be attributed to the effects of the interfacial shear forces. With an increase in temperature differences, the densities of the liquid film increased. This increased the wall-fluid, and vapour-liquid interfacial shear forces that increased the frictional pressure drops. Finally, both the measured and frictional pressure drops increased with an increase in temperature difference.

Conflict of interest
The authors declare that there is no conflict of interest.

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List of Figures

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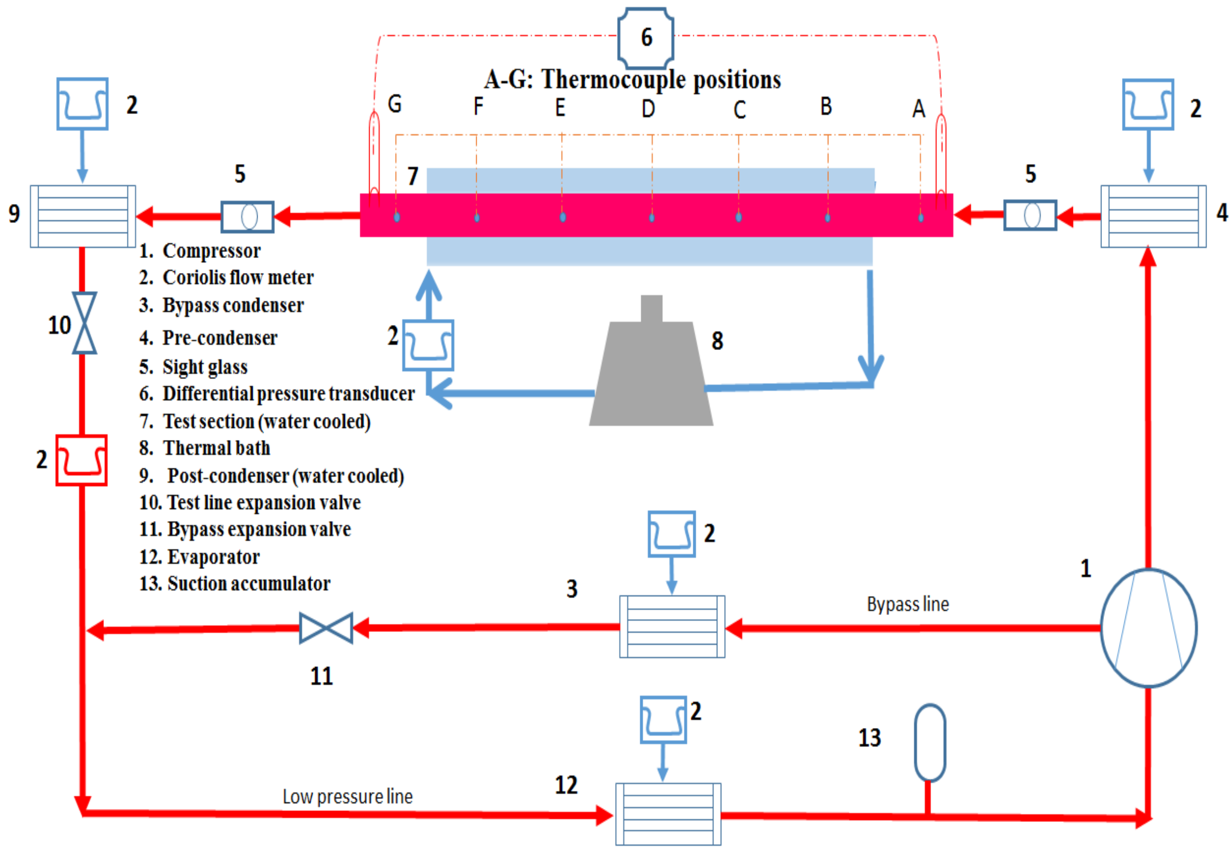

6
A-G: Thermocouple positions
G
F
E
D
C
B
A
7
5
5
2
2
2
2
2
2
9
4
8
10
1. Compressor
2. Coriolis flow meter
3. Bypass condenser
4. Pre-condenser
5. Sight glass
6. Differential pressure transducer
7. Test section (water cooled)
8. Thermal bath
9. Post-condenser (water cooled)
10. Test line expansion valve
11. Bypass expansion valve
12. Evaporator
13. Suction accumulator
1
3
Bypass line
11
13
12
Low pressure line

Figure 1

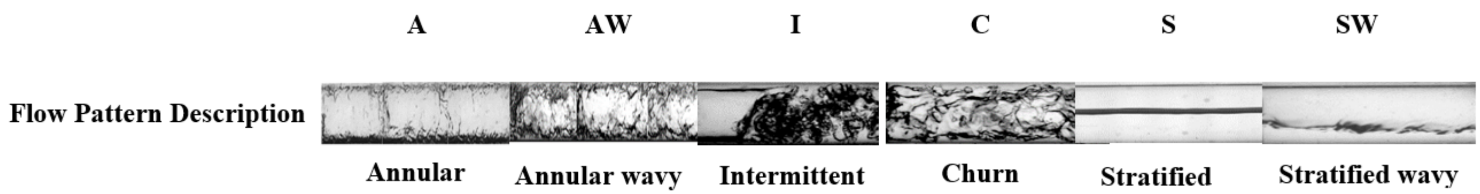


Figure 2

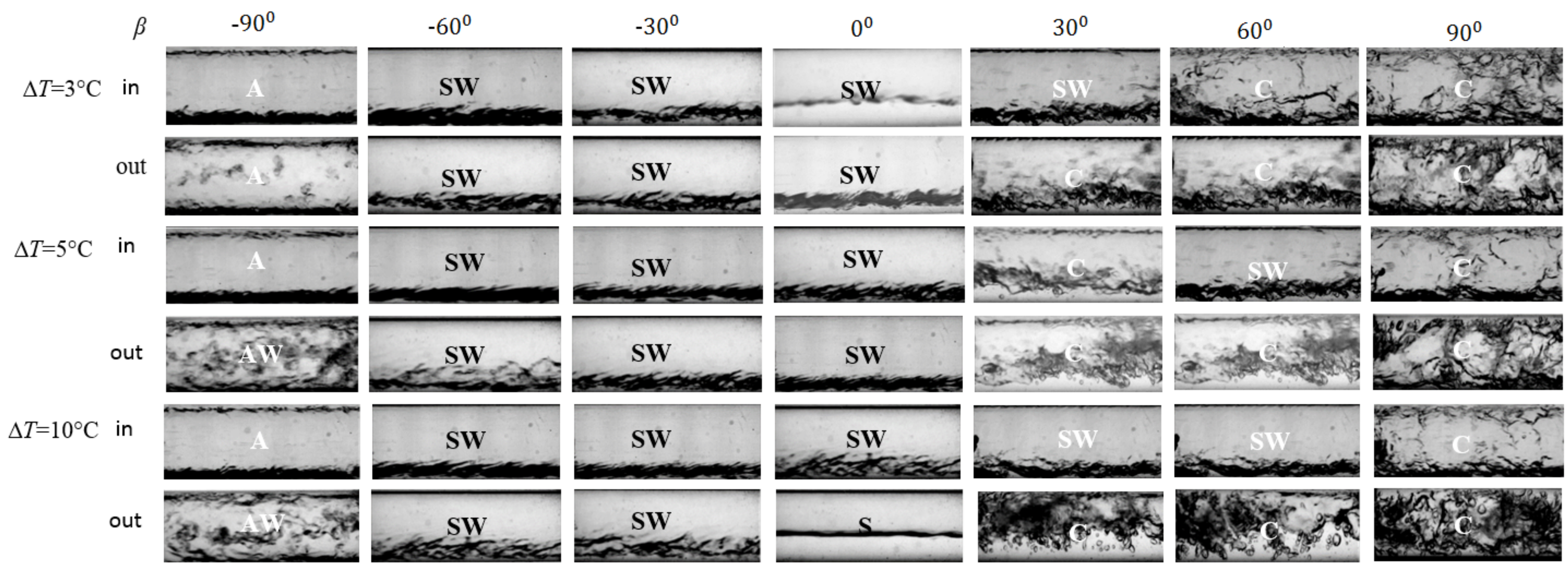


Figure 3

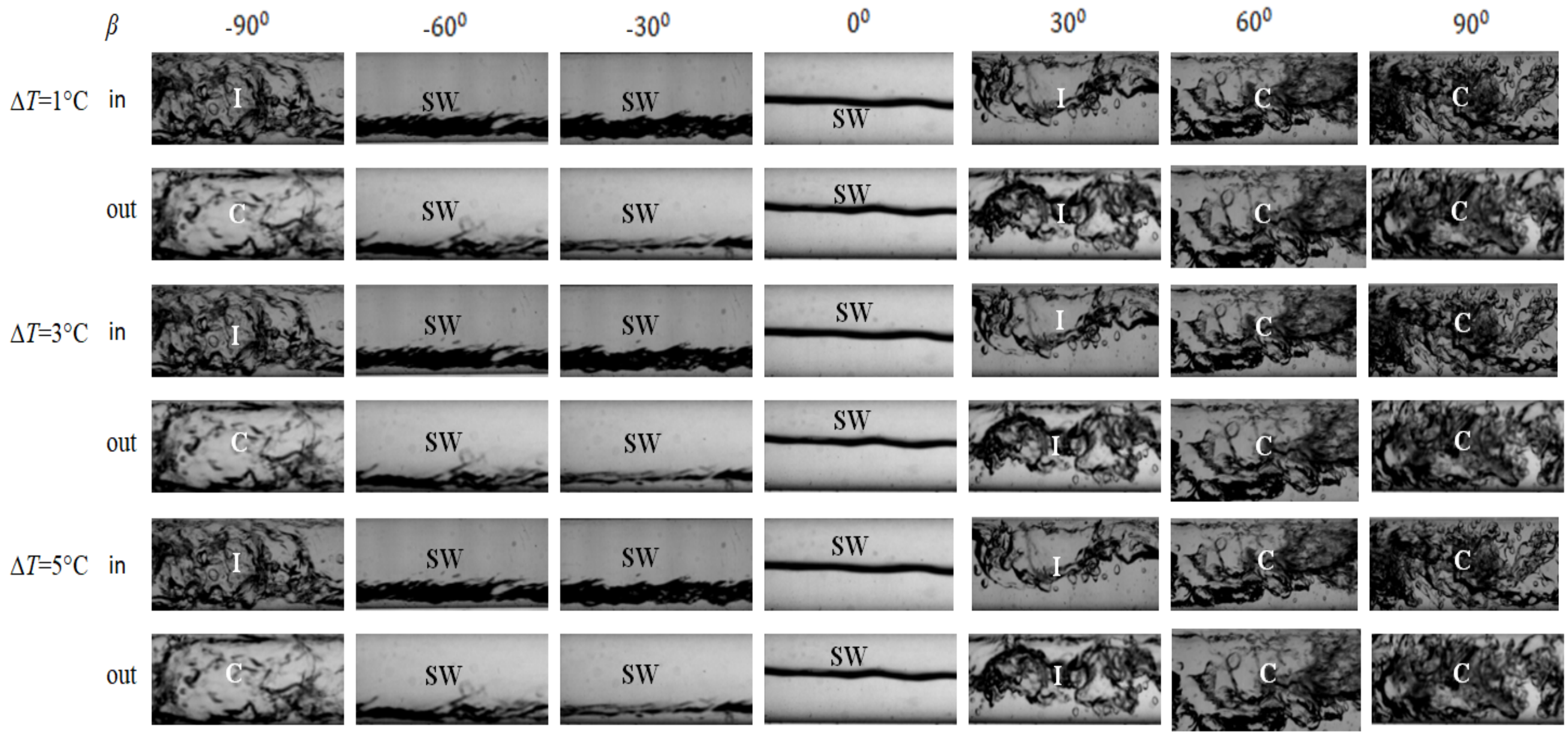
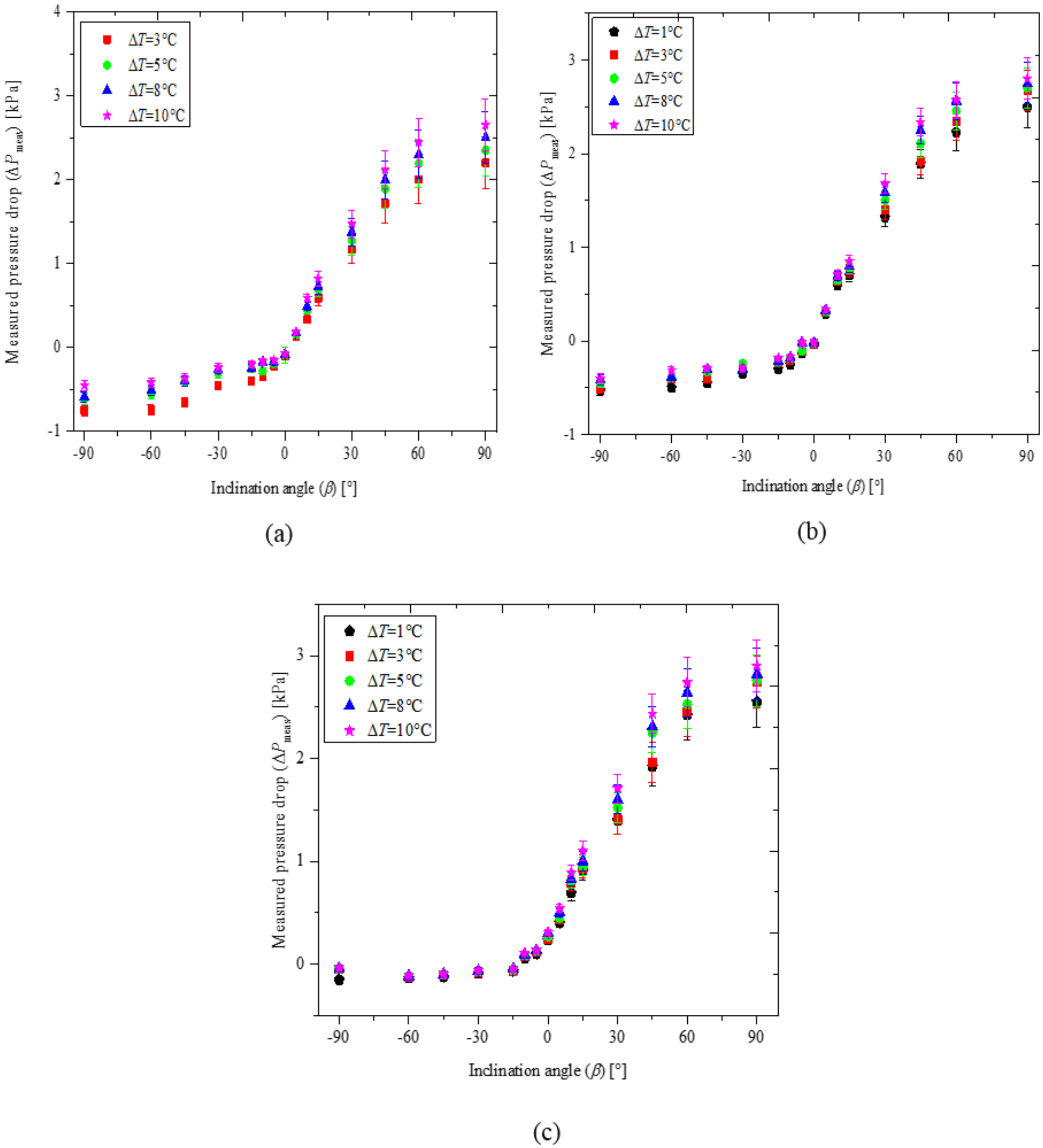


Figure 4



ΔT=3°C
ΔT=5°C
ΔT=8°C
ΔT=10°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
(a)
ΔT=1°C
ΔT=3°C
ΔT=5°C
ΔT=8°C
ΔT=10°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
(b)
ΔT=1°C
ΔT=3°C
ΔT=5°C
ΔT=8°C
ΔT=10°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
(c)

Figure 5

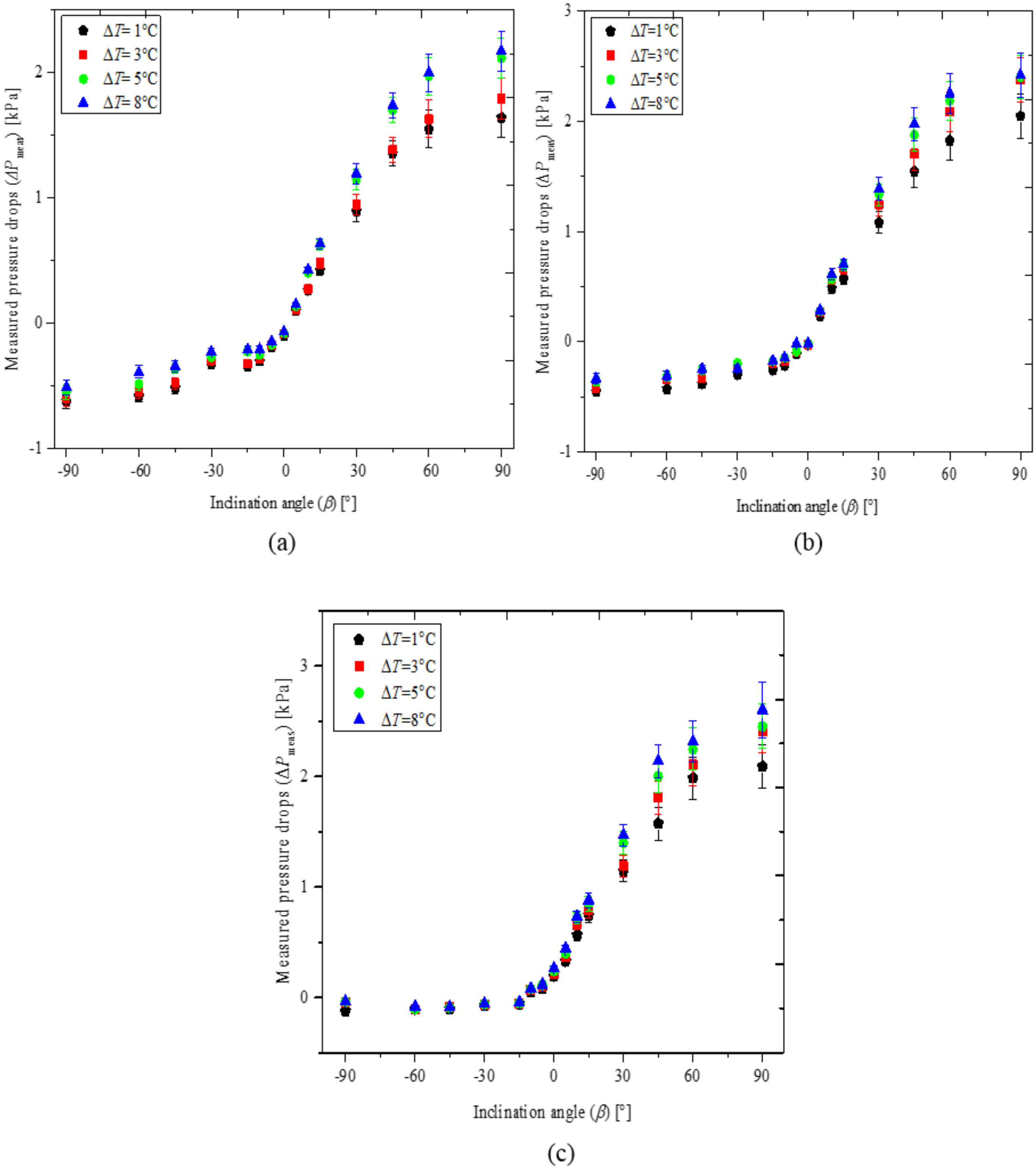
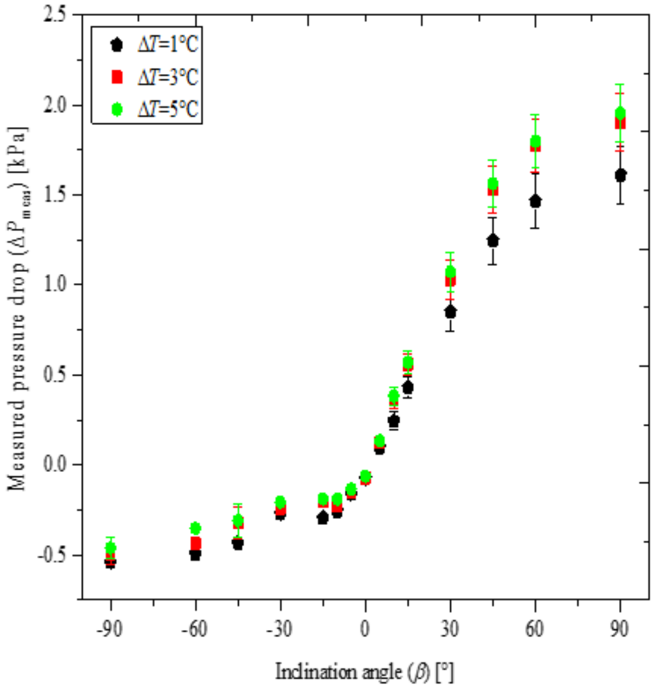
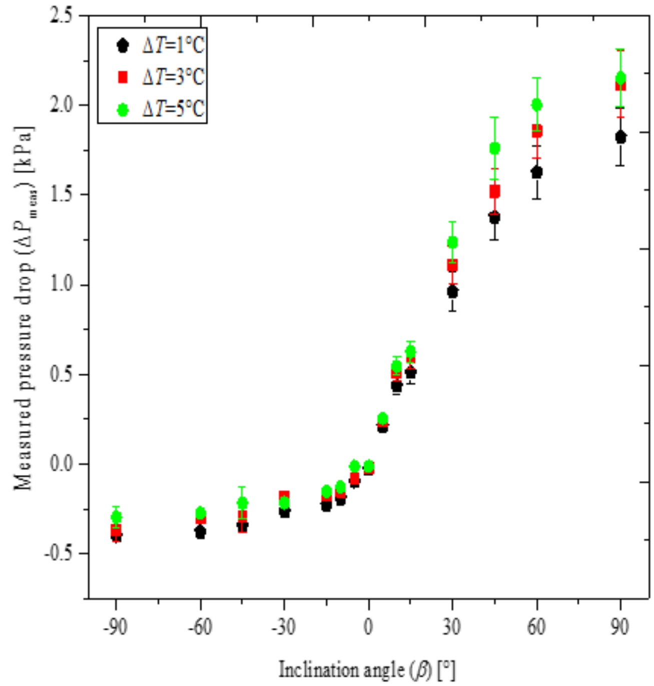

ΔT= 1°C
ΔT= 3°C
ΔT= 5°C
ΔT= 8°C
Measured pressure drops (ΔP_meas) [kPa]
Inclination angle (β) [°]
(a)
ΔT=1°C
ΔT=3°C
ΔT=5°C
ΔT=8°C
Measured pressure drops (ΔP_meas) [kPa]
Inclination angle (β) [°]
(b)
ΔT=1°C
ΔT=3°C
ΔT=5°C
ΔT=8°C
Measured pressure drops (ΔP_meas) [kPa]
Inclination angle (β) [°]
(c)

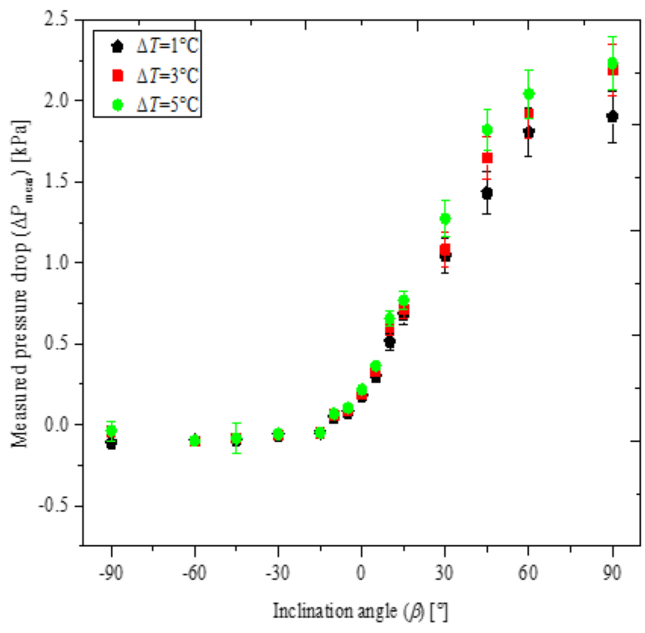
Figure 6


ΔT=1°C
ΔT=3°C
ΔT=5°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-90
-60
-30
0
30
60
90

(a)

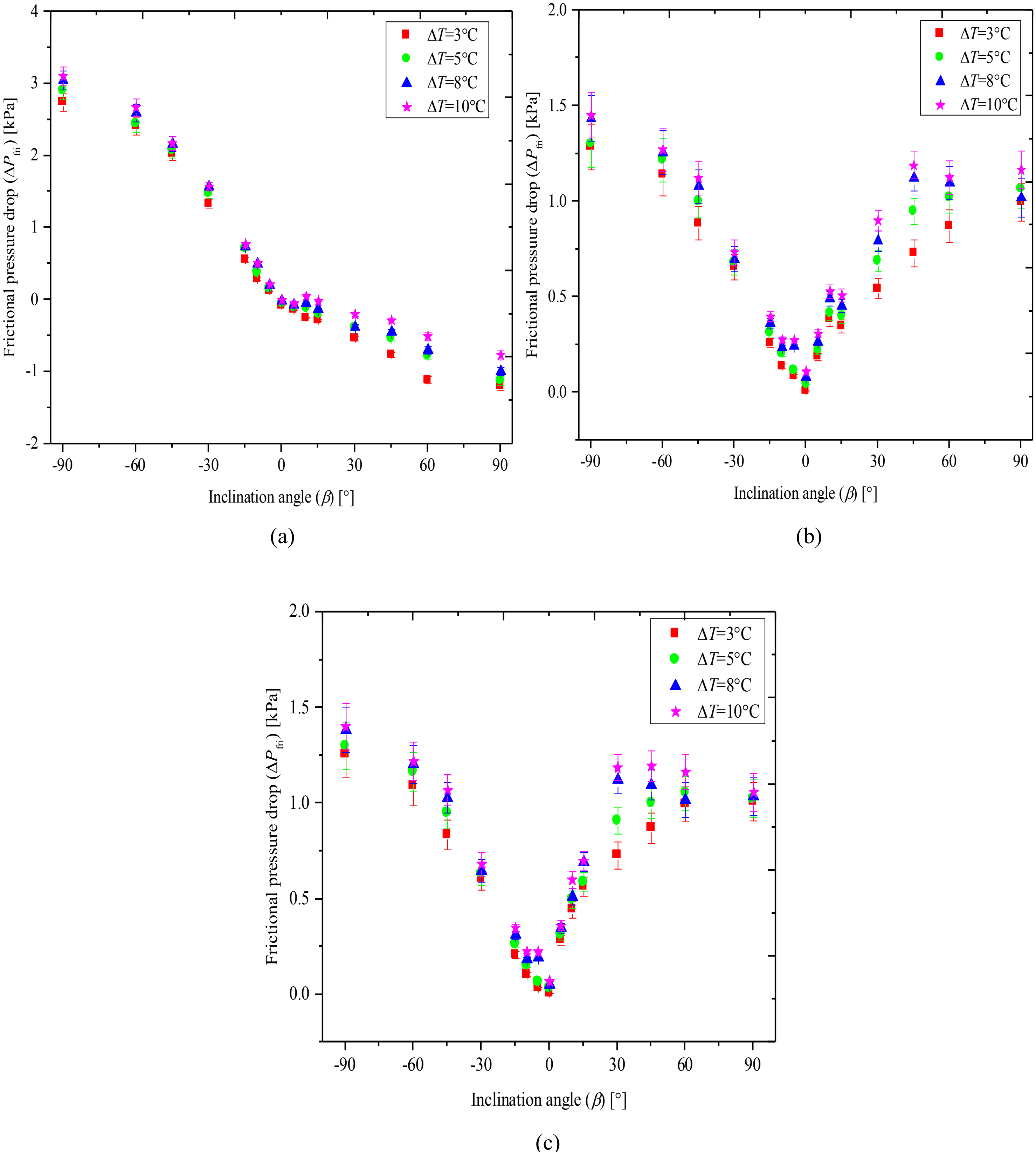

ΔT=1°C
ΔT=3°C
ΔT=5°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-90
-60
-30
0
30
60
90

(b)


ΔT=1°C
ΔT=3°C
ΔT=5°C
Measured pressure drop (ΔP_meas) [kPa]
Inclination angle (β) [°]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-90
-60
-30
0
30
60
90

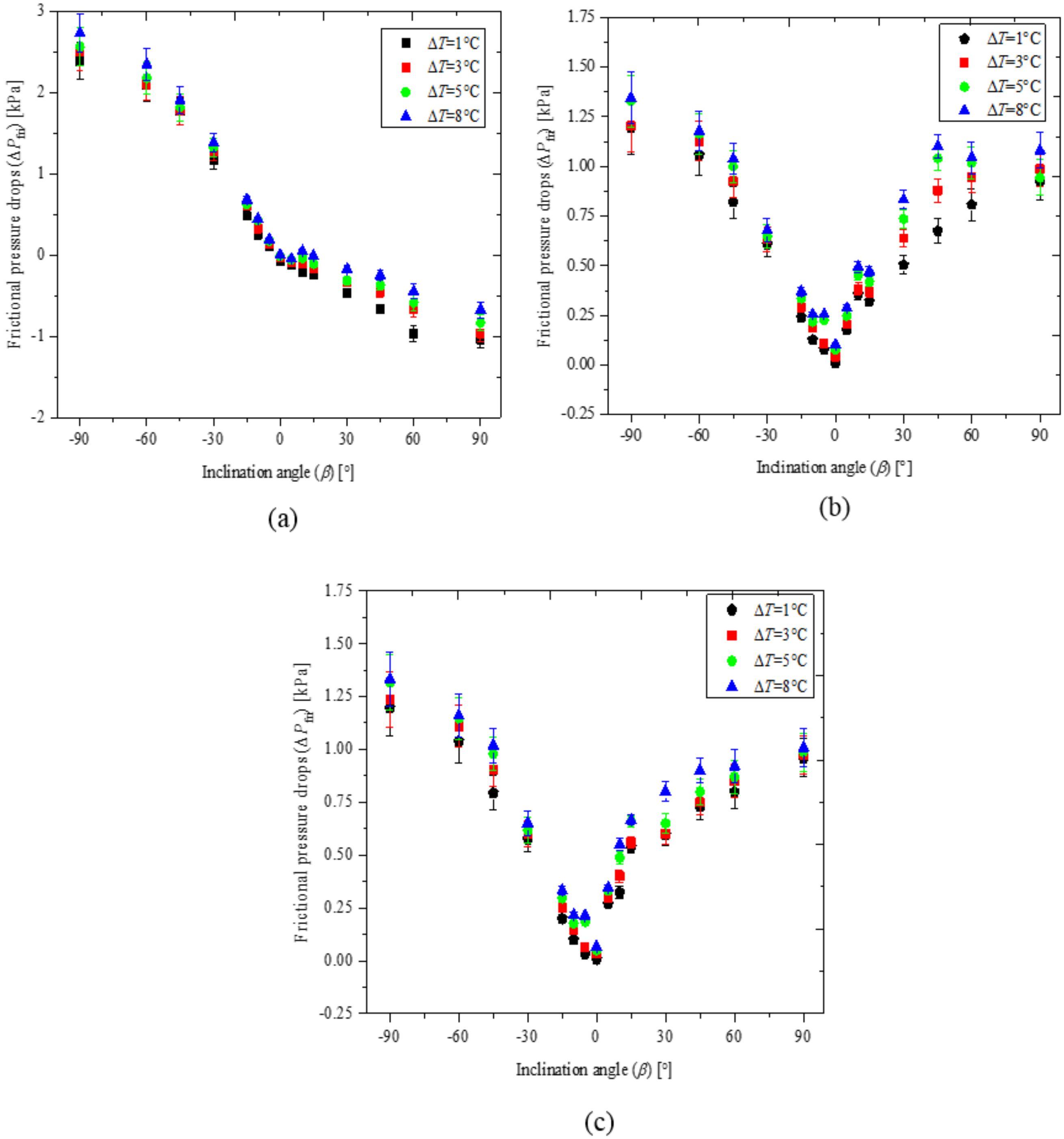
(c)

Figure 7



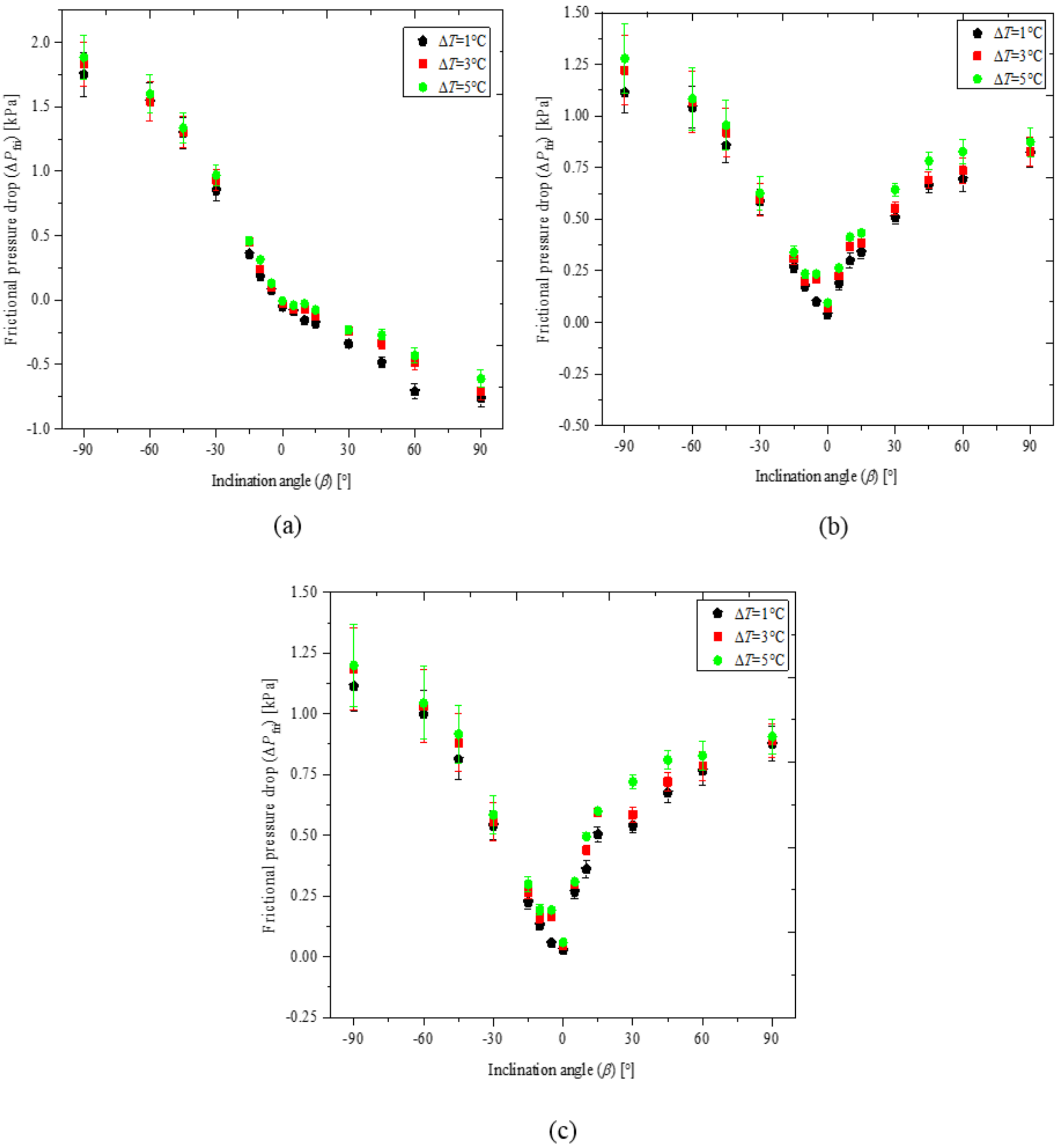
Frictional pressure drop (ΔP_{fri}) [kPa]
Inclination angle (β) [°]
ΔT=3°C
ΔT=5°C
ΔT=8°C
ΔT=10°C
(a)
(b)
(c)

Figure 8



Frictional pressure drops (ΔP_fri) [kPa]
Inclination angle (β) [°]
ΔT=1°C
ΔT=3°C
ΔT=5°C
ΔT=8°C
(a)
(b)
(c)

Figure 9



ΔT=1°C
ΔT=3°C
ΔT=5°C
Frictional pressure drop (ΔP_{fri}) [kPa]
Inclination angle (β) [°]
-90 -60 -30 0 30 60 90
2.0 1.5 1.0 0.5 0.0 -0.5 -1.0
(a)
1.50 1.25 1.00 0.75 0.50 0.25 0.00 -0.25 -0.50
(b)
1.50 1.25 1.00 0.75 0.50 0.25 0.00 -0.25
(c)

Figure 10

Table 1

Parameter	**Average**	**Minimum**	**Maximum**	**Standard deviation**
Condensation temperature	40.0 °C	39.6 °C	40.5 °C	0.28 °C
Saturation pressure	1 052 kPa	1 031 kPa	1 074 kPa	9.8 kPa
Energy balance (*EB*)	2.1%	0.2%	5.2%	1.2%

Table 2

G [kg/m²s]	x_m [-]	***β*** [°]	**Points**
200	0.5	−90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	15
300	0.5	−90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	15
400	0.5	-90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	15
			Total = 45 points

Table 3

G	ΔT	x_m	β	Points
[kg/m^{2}s]	[°C]	[-]	[°]	
50	1,3,5	0.10, 0.25, 0.5, 0.62, 0.75, 0.9	−90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	225
75	1,3,5,8	0.10, 0.25, 0.5, 0.62, 0.75, 0.9	−90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	300
100	1,3,5,8,10	0.10, 0.25, 0.5, 0.62, 0.75, 0.9	−90, −60, −45, −30, −15, −10, −5, 0, 5, 10, 15, 30, 45, 60, 90	375

Total = 900 points