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The Change of Flow Pattern from Stratified to Stratified-Wavy for Condensation in Wire on Tube Heat Exchangers

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ABSTRACT

Flow patterns inside wire-on-tube condensers with different refrigerant mass flow rates were studied in a theoretical study. In this study, tubes with diameters of 3.25 mm (3/16"), 4.83 mm (1/4") and 6.29 mm (5/16") were used. R-134a and R-600a cooling fluids were used at condensing temperatures of 54.4°C, 45°C, and 35°C. The results of this study were obtained using Equal Equation Solver (EES) software. The proposed model was able to predict the type of refrigerant flow pattern based on the limitations reported in previous studies. It was possible to distinguish four kinds of flow patterns: laminar, wavy laminar, plugged, and spiral. The first variation in flow pattern from laminar to wavy laminar flow found between 0.8 and 0.39, and a second variation in flow pattern found from wavy laminar flow to plug or slug flow between 0.15 and 0.05. For the refrigerant conditions, the condensation temperature did not affect the flow pattern. When using R-134a, the inner tube diameter had no effect on the flow pattern. Change occurs with R-600a as inner diameter was increased.

1. Introduction

Refrigerators and freezers are common household appliances around the world, and the thermal analysis of these appliances is important as shown in Mahdi *et al.,* [1] and Ali and Mahdi [2]. This equipment is made up of a compressor, condenser, throttling device, and evaporator. In order to build the appliances, reciprocating compressors with horsepower capacities of 1/12 - 1/3 are used. The compressors operate at a mass flow rate between 1 and 5.5 $kg.hr^{-1}$ of refrigerant. In this case, the condenser is wire-on-tube. The mass velocities of the refrigerant in this type of condenser are lower than 100 $kg.s^{-1}.m^{2}$. Several studies have indicated that stratified flow patterns change to stratified-wavy ones in condensers [3].

Typically, a condensation path in wire-on-tube heat exchangers starts with drywall desuperheating, moves to wetwall desuperheating, and ends with liquid subcooling. It is possible to divide the parameters that affect condensation into shear force flow and gravity force flow. Annular

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flows are controlled by shear forces, while stratified and stratified wavy flows are controlled by gravity forces. A flow pattern is influenced by heat transfer and momentum. Based on flow rate, quality, and fluid properties, the flow pattern type can be recognized. Liquid types and refrigerant types, as well as inner tube diameters, should all be considered.

The mass flow rate of refrigerant represented by mass velocities, and quality is determined by thermophysical properties and inner tube diameter, which determine the predominant flow pattern. There was previous evidence that stratified flow was observed only in tubes with a small inner diameter and low mass velocities [4]. Due to the interaction between the vapor and the fluid flow pattern, the flow pattern varies because of the instability of liquid and vapor velocities.

In their study, Taitel and Dukler [4] suggested a model of the horizontal motion of gas-liquids and a flow regime map. A five-type flow was found: smooth stratified, wavy stratified, intermittent (slug, plug, annular, bubble). The authors represented the transition by five dimensionless groups. Study by Breber *et al.,* [5] utilized the flow regime criteria to study pure refrigerants condensation in the horizontal tube. This study's conclusions are listed in Table 1.

Table 1
Limitations of Breber *et al.,* [5]

Flow type	Wallis dimensionless gas velocity J_g^*	Martinelli parameter Xtt
Wavy(W) or stratified(S)	< 0.5	<1.0
Intermittent(I)	<1.5	>1.5
Annual(A)	>1.5	<1.0
Bubble(B)	>1.5	>1.5

Tandon *et al.,* [6] also found two-phase flow patterns inside horizontal tubes. Working fluids in this study were R-12 and R-113, and the tubes were 4.8mm to 15.9mm in diameter and 0.61 m and 4.42 m in length. For this study, Wallis dimensionless gas velocity and void fraction were applied to obtain the flow patterns, and Table 2 lists its limitations.

Table 2
Limitations of Tandon *et al.,* [6]

Flow type	Wallis dimensionless gas velocity J_g^*	A void fraction $\frac{1-\alpha}{\alpha}$
Spray (Sp)	≥ 6	≤0.5
Annular and semi-annular (A)	$1 \leq J_g^* \leq 6$	≤0.5
Wavy (W)	≤1	≤0.5
Slug (SL)	$0.01 \leq J_g^* \leq 0.5$	≥0.5
Plug (PL)	≤ 0.01	≥0.5

Dobson and Chato [7] also studied the condensation phenomena inside pipes. El Hajal *et al.,* [8] and Thome *et al.,* [9] presented the two-phase flow as a function of mass velocity and vapour quality. They examined the transition areas of flow pattern types in relation to refrigerant types. The revised void equation, mass velocities, and heat transfer coefficients were determined using data from previous studies [4,5]. Table 3 presents the main limitations of these studies.

Table 3
Limitations of El Hajal *et al.,* [8] and Thome *et al.,* [9]

Flow type	Limitations
Annular	$G > G_{wavy}$, $G < G_{mist}$, $x > x_{IA}$
Intermittent	$G > G_{wavy}$, $G < G_{mist}$ $or\ G < G_{bubbly}$, $x < x_{IA}$
Stratified-wavy	$G_{strat} < G < G_{wavy}$ $fully\ stratified\ if\ G < G_{strat}$
Fully stratified	$G < G_{strat}$
Mist	$G > G_{mist}$

Koyama *et al.,* [10] studied experimentally two-phase flow in a smooth-walled pipe with a diameter of 7.5 mm and a length of 1024 mm. The researchers also studied two-phase flow in micro-finned tubes with diameters of 8.86 mm and lengths of 1015 mm. The study used R-134a to predict the void fraction and compared it with previous correlations.

Suliman *et al.,* [11] studied the condensation of R-134a inside a horizontal smooth copper tube. A mass flux range of 75-300 kg.s^{-1}.m^2 was covered by the study. In this study, the inner tube diameter was 8.38 mm and the length was 1.546 m. Saturation temperature was 40°C, and the quality of the vapor was 0.76-0.03. This study is based on previous studies by El Hajal *et al.,* [8] and Thome *et al.,* [9]. An analysis of the transient line between stratified wavy and annular waves was conducted.

Son and Lee [12] investigated the condensation of R-410A, R-22, and R-134a inside a horizontal copper tube. Moreover, the diameters of the inner diameters were 1.77, 3.36, and 5.35 mm, while the lengths of the inner diameters were 1220 mm, 2660 mm, and 3620 mm. During the study, mass flux ranged from 200 to 400 kg.s^{-1}.m^2 at 40°C saturation temperature. The data was tested using Taitel and Dukler [4] map in order to evaluate the type of flow pattern. This study examined a small diameter tube that had not been examined in previous studies.

In smooth horizontal copper tubes, Van Rooyen *et al.,* [13] calculated two-phase flow by using probabilistic time-fraction flow. Using R-22 and R-134a as working fluids, the inner tube diameter was 8.53 mm. The study covered a range between 200 and 700 kg.s^{-1}.m^2 mass flux. Thome *et al.,* [9] results were used as the basis for the theoretical part of the study.

By utilizing visual and experimental testing, previous studies, and correlations of heat transfer coefficients, Doretti *et al.,* [14] discovered a brand-new condensation map. A range of refrigerant mass velocities between 100 and 900 kg.s^{-1}.m^2. was measured in tubes with 8 mm diameter. A number of studies evaluating the test results from this study have been carried out, including Taitel and Dukler [4], Breber *et al.,* [5], Tandon *et al.,* [6], El Hajal *et al.,* [8] and Thome *et al.,* [9]. When low mass velocities were present, flow patterns were evaluated utilizing the difference between refrigerant and wall. A high mass velocity, on the other hand, was independent of temperature.

In their study, Sereda *et al.,* [15] investigated stratified flow condensation inside a 17mm diameter plain tube. In the study, a saturation temperature of 40 °C was used and the quality range was 0.95 to 0.23. There were 12 types of refrigerants used and the mass velocity range was 6-57 kg.s^{-1}.m^2. Heat transfer was determined using CFD.

Because of the surface tension between liquid and gas phases, the flow patterns inside small-diameter tubes vary from those inside large-diameter tubes. It is still unclear how the inner tube diameter affects the transient regime. There is a strong relationship between the stratified flow and the vapor temperature in the flow and the tube wall's temperature. This study aims to

i. The process of changing the refrigerant flow pattern from one type to another at low mass velocities flux is investigated. Choosing the correct heat transfer coefficient equation to calculate the heat rejected from the saturation part of the wire on tube heat exchanger was based on knowing the type of flow pattern.

ii. Formation and change of flow patterns based on tube diameter, condenser saturation temperature, mass velocity, and type of refrigerant (R-134a and R-600a).

2. Methodology
2.1 Modelling and Theoretical Analysis

Wire condensers have been theoretically analysed using the integration method of condensation inside tubes with Equal Equations Solver software. The recommended sizes of inner diameters for wire on tube condensers are 3.24 mm (3/16”), 4.826 mm (1/4”), and 6.299 mm (5/16”). The refrigerant mass flow rates are 1, 1.5, 2.5, 3.25, 4,4 and 5.5 ($kg.hr^{-1}$) which correspond to the size of the compressor (1/12-1/3 hp) used in manufacturing refrigerators and freezer home appliances. The current analysis also depends on the limitations that are presented in Table 3 in the introduction.

2.2 Assumptions

i. Equilibrium of the liquid and vapour flow under the effect of gravity, momentum, pressure gradient, acceleration, interfacial drag, and wall shear.
ii. Stable properties for liquid and vapour.
iii. Tube cross-sections are uniform in length and flow direction.
iv. Stratified flow: There is a vapour flow at the top and a liquid flow at the bottom of the tube. Smooth stratification occurs when liquid surfaces are smooth. Low vapour velocities and gravity control the regime cause this type to occur. The liquid-vapour interface is also smooth as a result of low gas velocities.
v. The liquid fills the tube and elongated bubbles appear when the liquid flows intermittently. This type of flow can be divided into plug and slug flow. During the end of the condensation process.

2.3 Void Fraction

A calculation of void fraction can be made according to Hajal *et al.,* [8]. As shown in Figure 1, El Hajal *et al.,* [8] and Thome *et al.,* [9] described the liquid and gas boundaries inside the tube and the upper angle not saturated by liquid stratification.

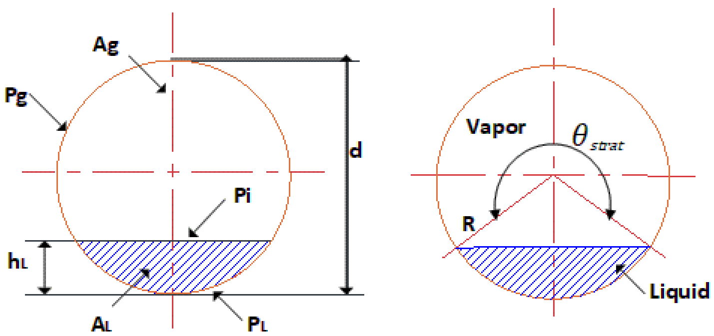

Fig. 1. Circular tube two-phase flow geometrical parameters

$$G = \frac{\dot{m}_r}{A_{ci}} \tag{1}$$

The homogeneous void fraction

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

Rouhani and Axelsson void fraction

$$\varepsilon_{ra} = \frac{x}{\rho_g}\left(\left[1 + 0.12(1-x)\left[\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right] + \frac{1.18(1-x)[g\rho(\rho_l-\rho_g)]^{0.25}}{G\rho_l^{0.5}}\right]\right)^{-1} \tag{3}$$

The logarithmic mean void fraction

$$\varepsilon = \frac{\varepsilon_h - \varepsilon_{ra}}{ln\left(\frac{\varepsilon_h}{\varepsilon_{ra}}\right)} \tag{4}$$

The start, wavy, mist, and bubbly mass velocity

The following equations are according to the circular tube's geometrical parameters for two-phase flow as in a Figure 1

$$A_l = A(1-\varepsilon) \qquad \rightarrow A_{ld} = \frac{A_l}{di^2}$$

$$A_g = A\varepsilon \qquad \rightarrow A_{gd} = \frac{A_g}{di^2}$$

$$\theta_{strat} = 2\pi - 2\left\{\pi(1-\varepsilon) + \left(\frac{3\pi}{2}\right)^{1/3}\left[1 - 2(1-\varepsilon) + (1-\varepsilon)^{1/3} - \varepsilon^{1/3}\right] - \frac{1}{200}(1-\varepsilon)\varepsilon[1 - 2(1-\varepsilon)][1 + 4(1-\varepsilon)^2 + \varepsilon^2]\right\} \tag{5}$$

$$A_{ld} = \frac{1}{8}[(2\pi - \theta_{strat}) - sin(2\pi - \theta_{strat})] \tag{6}$$

The following equations were used to determine the height of the liquid

$$h_{ld} = 0.5\left(1 - cos\left(\frac{2\pi - \theta_{strat}}{2}\right)\right) \tag{7}$$

The P_{id} geometric expression

$$P_{id} = sin\left(\frac{2\pi - \theta_{strat}}{2}\right) \tag{8}$$

The G start can be calculated from the below equation

$$G_{start} = \left\{\frac{(226.3)^2 A_{ld} \cdot A_{gd}^2 \cdot \rho_g\,(\rho_l - \rho_g)\mu_l \cdot g}{x^2\,(1-x)\pi^3}\right\}^{1/3} + 20x \tag{9}$$

3. Results and Discussion

Figure 2 illustrates the relation between mass velocity and start mass velocity via the quality of the refrigerant R-134a at condensation temperatures are 54.4, 45, 35°C and different inner tube diameter of 3.25, 4.826 and 6.299 mm. It shows the intersection between mass velocity G (solid line) and start mass velocity G start (dash line). For Figure 2(a), at low refrigerant flow rates (1, 1.5, 2.5) $kg.hr^{-1}$, there is no intersection between the mass velocity G and G start that is mean change from stratified to stratified-wavy, but when the flow increases the intersection is happening. The first intersection occurs when the flow rate is increasing greater than 2.5 $kg.hr^{-1}$ in two points; the first between quality values 0.8-0.4 at the beginning of the condensation depend on mass velocity value, which consists of flow rates 3.25 $kg.hr^{-1}$ and 4 $kg.hr^{-1}$. The flow pattern changes based upon the limitations in the previous studies [6,7]. There was a second intersection at the end of the condensation when the quality was between 0.15-0.05. The flow pattern turned from stratified wavy to plug flow.

When the flow rate of the refrigerant reaches higher than 5 $kg.hr^{-1}$, the intersection occurs at one point for the turn from stratified to stratified wavy only, and the flow pattern remains constant until the end of condensation.

Figure 2(b) has the same trend as Figure 2(a) but for inner diameter is 4.826 mm. The trends of the start mass velocity G start were close to the line of the mass velocity G at the higher refrigerant mass flow rate. It can be seen that no intersection happened between the mass velocity G and the G start. This result means no change from the stratified flow pattern to stratified wavy and the flow remained stratified because of the increase in the inner diameter from 3.25 to 4.826 mm. Figure 2(c) has similar curves to Figure 2(b), but the start mass velocity curves (G start) are different from the mass velocity curves (G). There is no intersection between the curves of the start mass velocity G, proving what is shown in references [6,7]. By enlarging the inner diameter of the tube to 6.299 mm, the flow stratifies based on the flow rate of the refrigerant.

There is no change for flow behaviour when the condenser temperature is 45 ℃ for R-134a as in Figure 2(d), Figure 2(e) and Figure 2(f). In addition, when the condenser temperature 35 °C as in Figure 2(g), Figure 2(h) and Figure 2(i). This means no effect for the condensing temperature on the change in flow pattern type from stratified to stratified- wavy flow.

For R-600a with a low condensation pressure, Figure 3 shows the relation between mass velocity and start mass velocity via the quality at condensing temperatures 54.4°C in Figure 3(a), Figure 3(b) and Figure 3(c). Figure 3(d), Figure 3(e), and Figure 3(f) were tested at 45 °C, while Figure 3(g), Figure 3(h), and Figure 3(i) at 35 °C. According to Figure 3, three inner diameters for the tube were tested: 3.25, 4.826, and 6.299 mm.

The effects of variable refrigerant flow inside the tube when the condensing temperature is 54.4 ℃ for refrigerant R-600a are shown in Figure 3(a). The change of the flow pattern starts when the flow is greater than 1 $kg.hr^{-1}$ for inner diameter 3.25 mm and quality (0.1-0.2). The most significant point is that the variation occurred from stratified to stratified-wavy flow for R-600a at flow rate higher than 1.5 $kg.hr^{-1}$. When comparing Figure 2(a) with a flow rate greater than 2.5 $kg.hr^{-1}$ of R-134a, it can be that the change from S to S-W occurs early when the refrigerant gas is changed from one with a lower observed condensing pressure to one with a higher condensing temperature. The flow pattern changes at the end of the condensation from stratified-wavy to plug appear when the quality between (0.22-0.05).

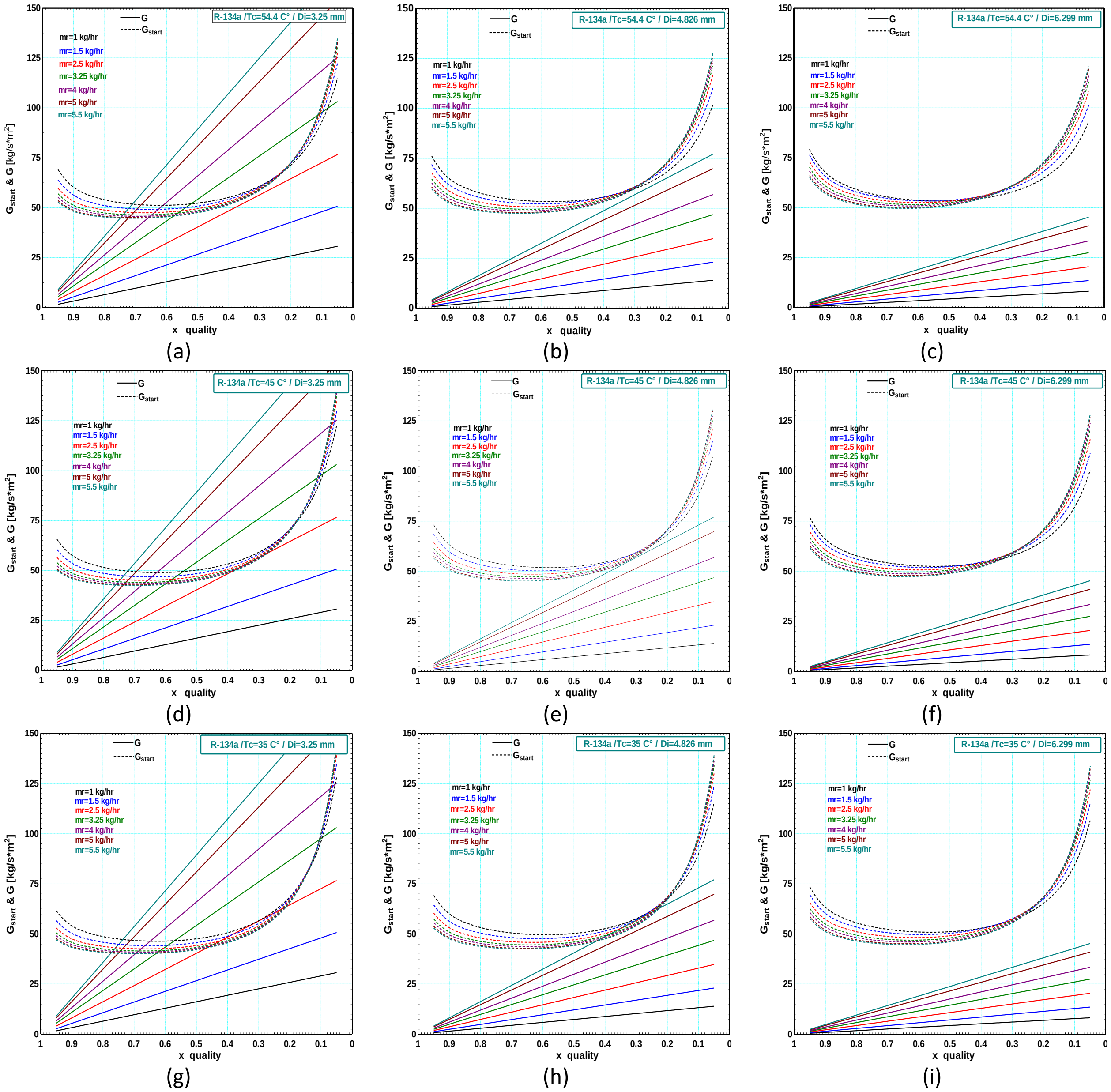

Fig. 2. The relation between the quality and G, Gstart for R-134a for inner diameters: 3.25, 4.826 and 6.299 mm respectively, and at different condensation temperatures: ((a), (b) and (c) at 54.4℃), ((d), (e) and (f) at 45℃), and ((g), (h) and (i) at 35 °C)

Figure 3(d), Figure 3(e), and Figure 3(f), and Figure 3(g), Figure 3(h), and Figure 3(i) show similar trends for R-600a at condensation temperatures of 45 and 35°C, respectively. Based on these results, an increase in internal diameter results in a change from SW to S flow patterns. Flow pattern behaviour was not affected by condensation temperature, however.

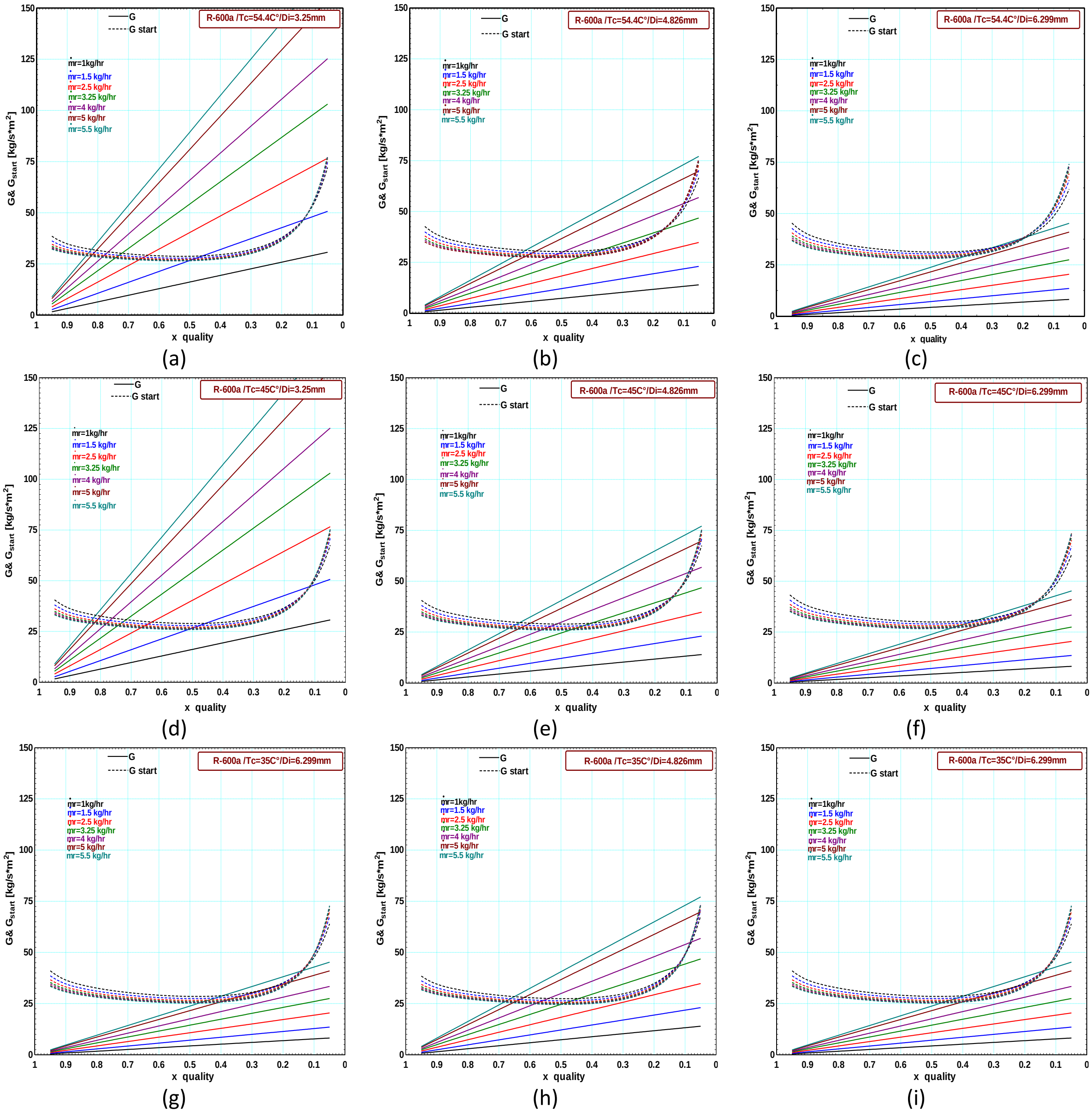

Fig. 3. The relation between the quality, G and G start for R-600a for inner diameters: 3.25, 4.826, and 6.299 mm respectively, and at different condensation temperatures: ((a), (b), (c) at 54.4℃), ((d), (e), (f) at 45℃), and ((g), (h), (i) at 35 ℃)

Despite operating at the same condensation temperature, R-134a and R-600a have different condensation pressures. According to this study, the flow pattern depends on the condensing temperatures and refrigerant pipe diameters. Using the Preber map, Figure 4 shows the study outcome data's location within the wavy and stratified flow regime between 0.95 and 0.15 quality. When the quality is between 0.15 and 0.05, condensation ends.

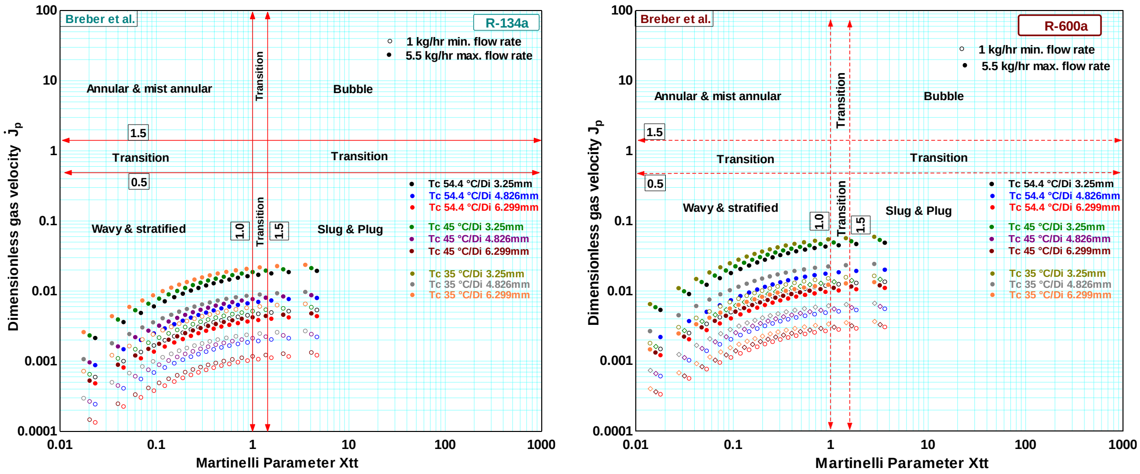

Fig. 4. Comparing the study results with Breber *et al.,* [5] map for R-134a and R-600a

According to the El-Hajal *et al.,*'s [8] map shown in Figure 5, all data are displayed as stratified flow except for the high mass velocity for the small inner diameter 3.25 mm of three condensation temperatures, which is displayed as stratified-wavy.

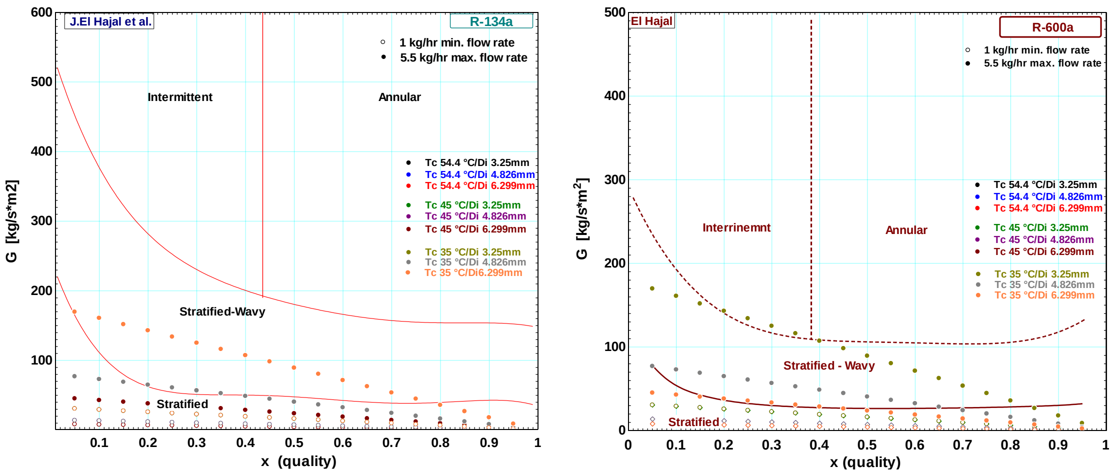

Fig. 5. Comparing the current study results with El Hajal *et al.,* [8] map for R-134a and R-600a

The present results were compared with the Tandon map to form a third conformation (Figure 6). According to the results of this study, a wavy system is formed by the laminar flow (as defined on the map) and the end of condensation in the slug and plug flow ruling system. Data for low mass flow rates are at the bottom of the undulating regime, while data for high mass flow rates approach the annular regime.

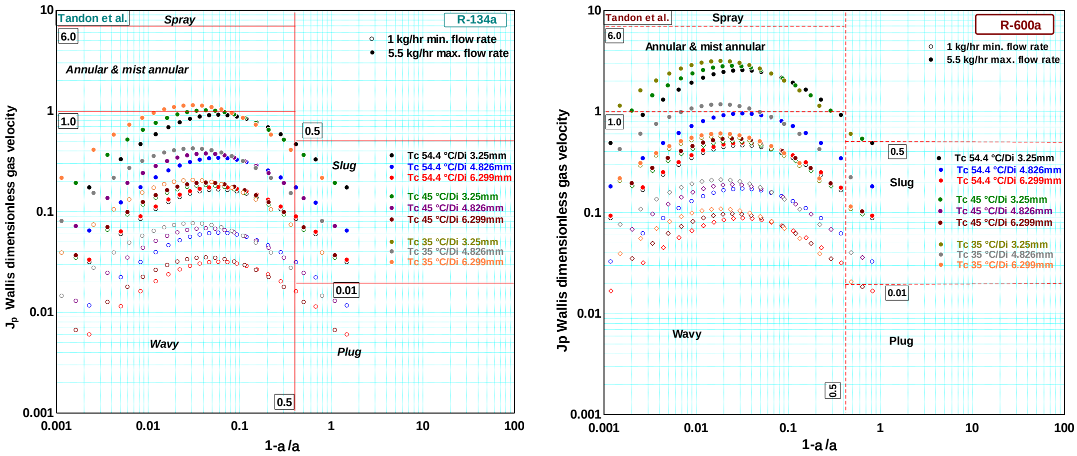

Fig. 6. Comparing the study results with Tandon *et al.,* [6] map for R-134a and R-600a

In Figure 7, the results of the current study are compared with Taitel and Dunkle approach. As a result of the temperature difference between the refrigerant and the wall, all results data populate the gravity flow regime. Flow patterns associated with gravity include laminar, undulating, and intermediate (slugs and plugs) flows.

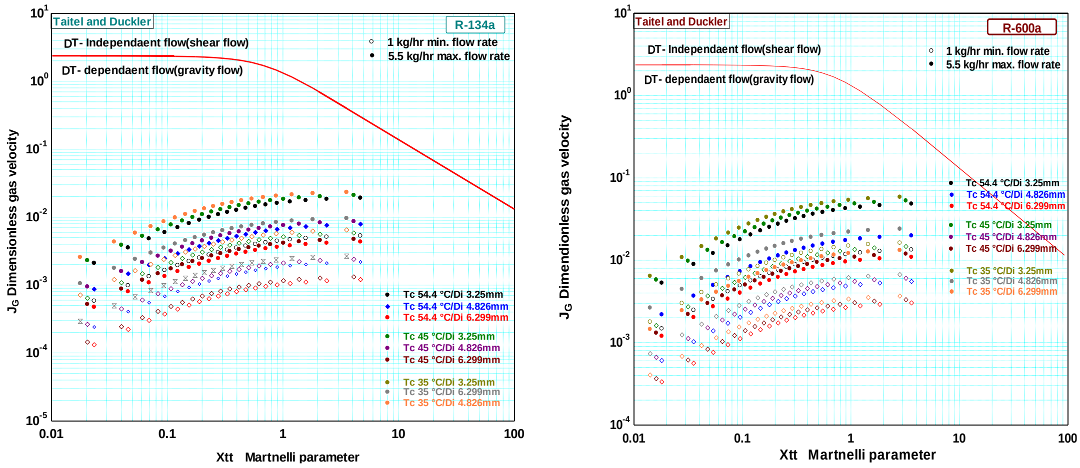

Fig. 7. Comparing the study results with Taitel and Dukler [4] map for R-134a and R-600a

4. Conclusions

According to the integral analysis by EES software and the findings results shown in the Figures, the significant points from this study are summarized below

i. The theoretical analysis used in this study, based on an integration method, shows that it can identify the transient regimes for flow from stratified to stratified wavy, and from stratified or stratified wavy to plug or slug flow at the end of the condensation.
ii. The alteration from stratified to stratified wavy was happened in the range of quality 0.8 to 0.39, while the change from stratified wavy to plug or slug flow was found at quality 0.15 to 0.05.
iii. Changes from S to SW occur early for small inner diameters and later for larger inner diameters.
iv. It was found that the condensation temperature had no effect on the change of the flow from stratified to stratified wavy or plug to slug. This was true for different inner diameters and refrigerant types.

v. The effect of the refrigerant type showed that the change in flow pattern from S to SW can be done early with R-600a than R-134a for same inner diameter size.

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