

Experimental investigations into the impact of the void fraction on the condensation characteristics of R134a refrigerant in minichannels under conditions of periodic instability

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Abstract This paper presents the results of experimental investigations of condensation of R134a refrigerant in pipe minichannels with internal diameters 0.64, 0.90, 1.40, 1.44, 1.92 and 3.30 mm subject to periodic pressure instabilities. It was established that as in conventional channels, the displacement velocity of the pressure instabilities distinctly depends on the frequency of their hydrodynamic generation. The void fraction distinctly influences the velocity of the pressure instabilities. The form of this relationship depends on the internal diameter of the minichannels and on the method of calculating the void fraction.

Keywords: Condensation; Minichannels; Periodic instabilities; Void fraction

Nomenclature

- a – sound phase velocity, m/s
- d – internal diameter of minichannel, m
- f – frequency, s⁻¹
- G – mass flux, kg/m²s
- g – gravitational acceleration, m/s²
- L – length of minichannel, m

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l	–	distance between the pressure sensors, m
\dot{m}	–	mass flow rate, kg/h
p	–	pressure, MPa
S	–	slip ratio
T	–	temperature of the refrigerant, °C
T_s	–	saturation temperature, K
w	–	flow velocity, m/s
v_p	–	pressure signal propagation velocity, m/s
V	–	volume, m
x	–	steam quality
Re_l	–	liquid Reynolds number
We	–	Weber number

Greek symbols

μ	–	kinematic viscosity, m ² /s
Φ	–	void fraction
ρ	–	density, kg/m ³
τ	–	time, s
$\Delta\tau$	–	time interval, s

Subscripts

c	–	state in which the cut-off valve is shut
e	–	equilibrium
f	–	frozen
g	–	gaseous phase
H	–	homogeneous
o	–	state in which the cut-off valve is open
in	–	cross-section of the inlet, where the measurement begins
l	–	liquid phase
out	–	outlet cross-section
s	–	condensation
w	–	internal surface

1 Introduction

Modeling wave phenomena in two-phase flows containing both vapor and liquid is of essential significance. The literature covers mathematical models and correlations that describe wave phenomena in two-phase flows in conventional channels. At the same time, there are few published papers [5,14,24,27] that consider this problem for minichannels. These publications usually deal with boiling instabilities and treat condensation less frequently. An important question is whether those models that have been verified in conventional channels can be applied to phase changes that are realized in minichannels.

Continuous models are commonly applied to two-phase flows in conventional channels and can be categorized as follows:

- homogeneous models, where the two-phase flow possesses the properties of a mixture in which the most important features of both phases overlap,
- fluid models, which take into account the varying velocities of the two phases (the so-called slip ratio).

Depending on the state of the refrigerant in the two-phase system, the models can also be categorized as equilibrium, quasi-equilibrium and non-equilibrium models.

The heat exchange conditions during condensation (boiling) of a fluid in channels depend on the characteristics of the channel's surface and other basic parameters including the saturation temperature (which depends on the saturation pressure, heat flux density, mass flux and quantities that describe the fractions of the flow in the liquid and gaseous phases, known as the mass or volume fractions).

In the two-phase processes of condensation or boiling of a fluid in channels, a very important part is played by the void fraction, which defines the volume fraction of the vapor phase in the following form:

$$\phi = \frac{V_g}{V_l + V_g}, \quad (1)$$

where V_l and V_g are the volumes occupied by the liquid and vapor phases, respectively, and $V_l + V_g = V$ is the total volume.

Other characteristic quantities are required to compute the void fraction, including the following:

- slip ratio [6,20,26,32],
- Lockhardt-Martinelli parameter [11,18,29], and
- flow structure parameters [10,12,13,15].

Determining the void fraction in mini and microchannels is difficult, which is why so few papers have been published concerning this issue. The authors have described computing the void fraction from an analysis of a mechanism of vapor bubble formation [16,21]. Additionally, a method of visualizing flow structures was implemented by processing the registered image using, for example, neutron radiography [2,21].

Some two-phase models account for the occurrence of slip ratio, which is defined as $S = w_g/w_l$, where w_g and w_l are the velocities of the gaseous and liquid phases, respectively. If $S = 1$, then there exists homogeneous flow, which means that both phases flow with the same velocity. The void fraction for such a flow is called homogeneous. During two-phase flow in minichannels the value of the slip is small [9], and appears in bubble, slug and annular flow patterns. An experimental method for determining the void fraction in minichannels with hydraulic diameters of 0.74–3.07 mm was presented in paper [2]. The authors used air and a water mixture with different glycerol concentrations. The experimental results obtained in this research were verified using correlations that make use of the slip ratio [23]. The authors presented their computational model for determining the void fraction in [23]. Paper [28] reviews the correlations that are most frequently used to calculate the void fraction in two-phase flow in minichannels and found that the experimental and computational results were in best agreement when the homogeneous correlation is used. A similar listing of correlations for computing the void fraction was provided in a paper by the author [8], which considered conventional channels as well as smooth and finned channels. The results of experimental investigations of condensation and boiling of the refrigerants R134a and R404A in smooth channels are presented in [32]. The authors proposed their own empirical correlation for calculating the void fraction under these conditions.

Analyzing publications by various authors reveals that, at present, there is no preferred method to determine the void fraction in conventional channels or, particularly, in mini-channels. Nevertheless, the value of void fraction is very important to the description of phase change in flows through channels.

Two-phase flows in conventional channels and minichannels are accompanied by a number of types of instabilities, which are generally wavelike in nature [1,3,4,30]. Instabilities may be static or dynamic. Static characteristics are usually related to changes in the flow structure of two-phase media, while dynamic disturbances result from external interactions, e.g., hydrodynamic or thermal interactions. The “wavy nature” of the system may manifest as oscillations in the mass flux of the refrigerant, which results in pulsations in the pressure, temperature, density, etc.

In contrast to single-phase media, two-phase mixtures are characterized by energy dissipation and a dispersive nature related to the frequency of any disturbances [3,4]. Dissipative interactions influence the irreversibility

of the flow process and usually lead to instability in the state of a two-phase system. In two-phase media (like vapor and liquid), disturbances may “upset” the thermodynamic equilibrium state. The relaxation time, i.e., the time necessary for the system to return to its equilibrium state, may be close to the period of changes in the parameters of the medium during the flow. In some cases, the system does not return to the initial equilibrium state, even when external interactions are removed [3,4].

Knowing the behavior of a system subjected to dynamic interactions in the form of disturbances to the two-phase condensation state is important for both fundamental and commercial reasons. The instabilities in the condensation process that occur in minichannels not only lead to reduced energy efficiency but also may influence the continuity of operating a refrigerating device that includes a compact condenser.

2 Experimental investigations

The experimental investigations concerned determining the influence of the void fraction Φ on the description of periodic instabilities in the condensation of the refrigerant R134a in pipe minichannels with the internal diameters $d_w = 0.64, 0.90, 1.40, 1.44, 1.92$ and 3.30 mm. Instabilities in the condensation process were induced by generating external hydrodynamic disturbances. Periodic instabilities at a constant frequency were produced in the system. The primary quantity in the description of this type of instability is the propagation velocity of the pressure signal in the minichannel, which is denoted with the symbol v_p . The velocity of the pressure signal propagation depends not only on the thermodynamic parameters of the process but also on the void fraction.

2.1 Testing facility and research methodology

The experimental tests were conducted at a testing facility that was designed for this purpose; its schematic diagram is presented in Fig. 1.

The following quantities were measured on the testing facility:

- the pressure distribution p_s of the R134a refrigerant along the flow path through a straight-axis minichannel;
- the refrigerant temperature profile along the flow path through the pipe minichannel;

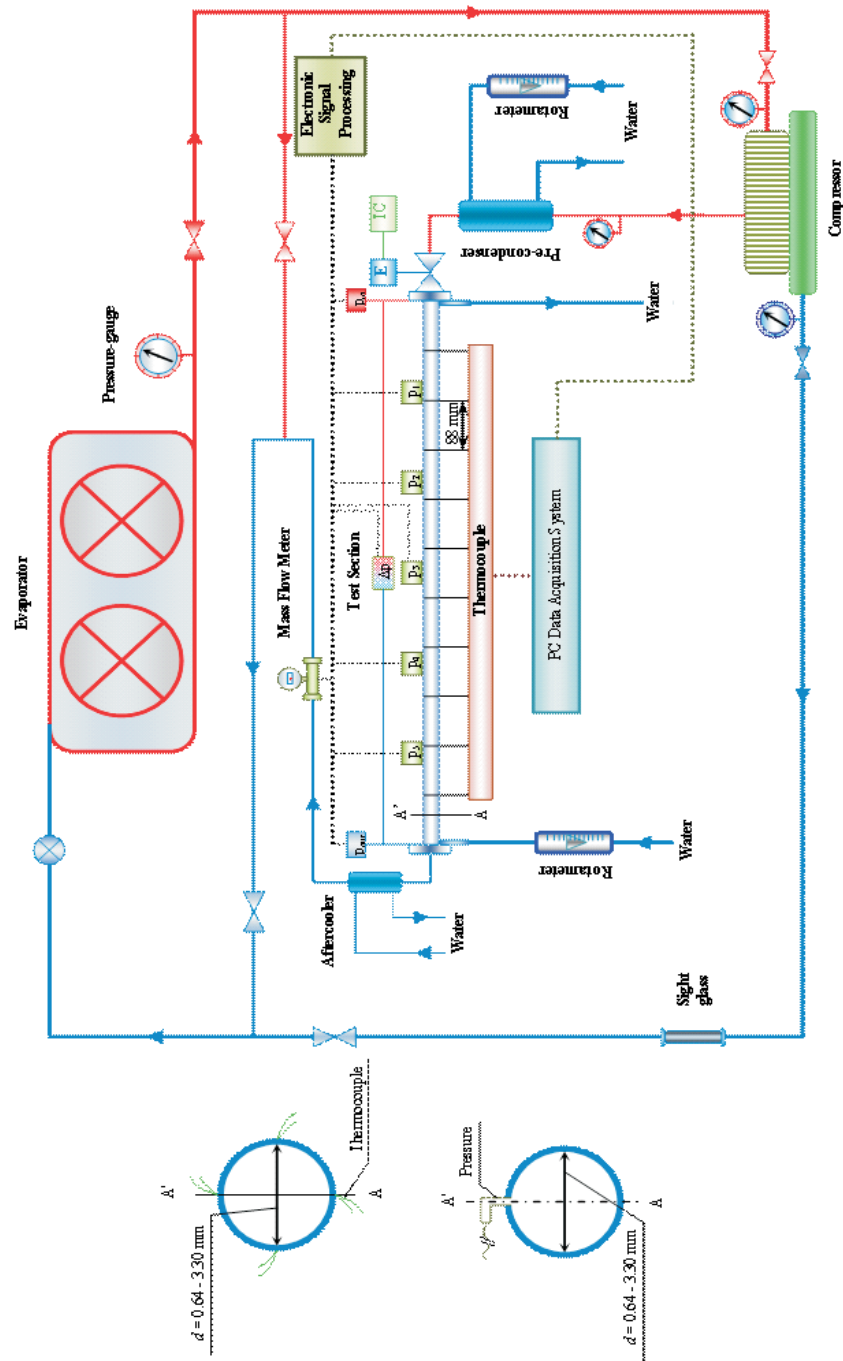


Figure 1. A schematic of the experimental facility: E – valve, TC – timer, p_1 , ..., p_5 – pressure transducers.

- the pressure of the refrigerant at the inflow and outflow from the measured pipe section, denoted p_{in} and p_{out} , respectively;
- the temperature of the refrigerant at the inflow and outflow from the measured section, denoted T_{in} and T_{out} , respectively;
- the mass flow rate of the refrigerant \dot{m}_{R134a} and the water \dot{m}_{H_2O} .

The investigations were conducted with the following parameters:

- refrigerant mass flux $G = 100\text{--}4100 \text{ kg}/(\text{m}^2 \text{ s})$,
- refrigerant saturation temperature $T_s = 20\text{--}55 \text{ }^\circ\text{C}$,
- disturbance frequency $f = 0.20\text{--}5 \text{ Hz}$.

The tests were performed with a constant initial refrigerant mass flow rate \dot{m}_{R134a} . Five piezo-electric pressure sensors were installed at evenly spaced intervals along the length $L = 880 \text{ mm}$ of the minichannel's measurement section. A computer system was used to measure and record voltage signals from the pressure and temperature sensors and from the flow meter. The computer system consists of the following components:

- K-type thermocouples, which were attached to the walls of the minichannels (for every of them, individual characteristics were made with the measuring error having been set on the level of $\pm 0.05 \text{ }^\circ\text{C}$). These were connected to a USB PersonalDaq/3000 measuring module with a PDQ30 extension and took measurements at a frequency of 0.03 Hz ;
- piezoresistant pressure sensors (Cerabar TPMP131) with an accuracy rating of 0.75% . These sensors were interfaced to the measuring module;
- a mass flowmeter (Coriolis Promass 80A) with an accuracy rating of 0.15% .

Prior to the start of the primary investigations, the system was brought to a steady state. The initial value of the R134a refrigerant mass flow rate was measured. In this state, external periodic disturbances were introduced by closing and opening the electromagnetic valve E, which was installed at the feeding portion of the measuring section of the minichannel (Fig. 1) and was controlled by means of a Siemens LOGO 230R time controller.

The concept of "periodically generated disturbances" is to be understood as periodic changes in the feeding of refrigerant into a pipe minichannel that

results from changes in the opening time τ_o and the closing time τ_c of the valve E, which was installed at the inlet to the measuring section. In a given measuring section, the condition $\tau_o = \tau_c$ was maintained. The opening and closing times were always incremented by 0.05 s in each consecutive series. The initial closing and opening times were $\tau_o = \tau_c = 0.1$ s. These choices were the results of an empirical determination of the lowest frequency range in which the generated disturbances produced observable impacts on the condensation process in the pipe minichannel.

The sum of the valve opening and closing times determines the frequencies of the generated disturbances f [Hz] according to the following equation [10,11]:

$$f = \frac{1}{\tau_o + \tau_c} \text{ [Hz]}, \quad (2)$$

where τ_o and τ_c denote the opening and closing times, respectively, of the valve at the refrigerant inlet to the minichannel and are expressed in seconds.

The hydrodynamic disturbances produced pressure and temperature oscillations at the minichannel wall. The propagation velocity of the pressure signal along the length of the measurement section was described with the following equation:

$$v_p = \frac{l}{\Delta\tau_p}, \quad (3)$$

where $\Delta\tau_p$ denotes the time between observations of a pressure change by two pressure sensors located at distance l from each other.

The boundary values of the propagation velocity v_p of disturbances in pipe minichannels were experimentally established. These quantities corresponded to the phase velocities that are defined in literature as the “frozen” and “equilibrium” phase velocities, denoted as a_f and a_e , respectively. The “frozen” velocity corresponds to the largest pressure instability displacement velocities v_p as the disturbance frequency $f \rightarrow \infty$. The “equilibrium” velocity constitutes the smallest value of the velocity v_p as the frequency $f \rightarrow 0$ [1,3].

2.2 Results of experimental tests and their analysis

Figure 2 presents the experimentally established dependence of the pressure signal propagation velocity v_p upon the frequency f in the R134a refrigerant. It is evident that the characteristics of this relationship depends on the diameter d_w of the minichannel. This interaction was also confirmed in

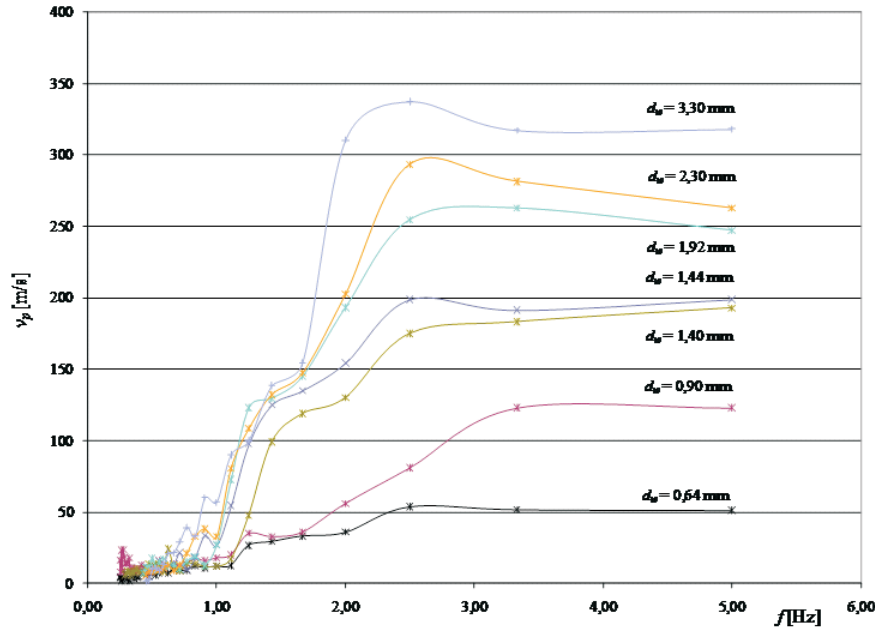


Figure 2. Result of experimental investigations of the dependence of the pressure signal propagation velocity on the frequency of disturbances in the R134a refrigerant; the internal diameters of the pipe minichannels were $d_w = 0.64$; 0.90 ; 1.40 ; 1.44 ; 1.92 ; 3.30 mm.

other experimental investigations conducted by the authors [1,17,30].

Figure 3 shows the relation between the sound velocity a and the frequency f of the two-phase flow in conventional channels. The sound velocity increases monotonically as the frequency increases from its smallest value $a = a_e$ (the “equilibrium” velocity) and asymptotically approaches the velocity a_f (the so-called “frozen” velocity) [1,4,30]. This behavior can be obtained through mathematical modeling of two-phase flows [1,30] that considers the wavy nature of phase changes. It should be noted that the minichannels (Fig. 2) and the conventional channels (Fig. 3) exhibit similar characteristics.

It is evident from the analysis of the experimental results that the periodical disturbances cause the refrigerant pressure to oscillate as it flows through the pipe minichannel. A time delay was observed in the reactions of the pressure sensors, meaning that the pressure changes propagate with a finite velocity when the shut-off valve is opened or closed and confirming

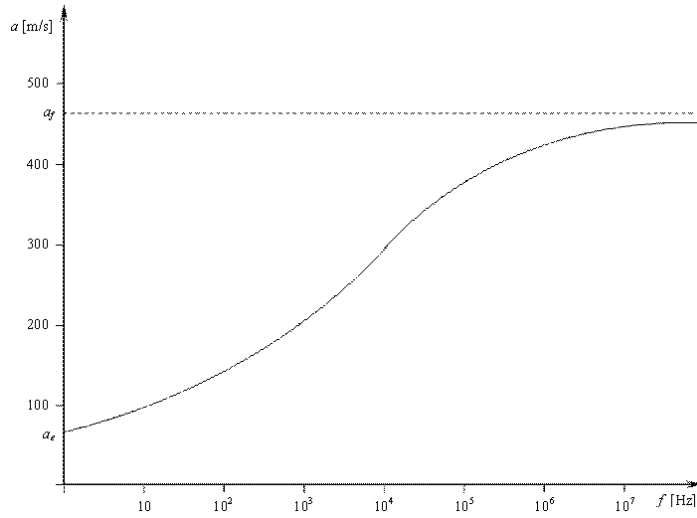


Figure 3. The dependence of the sound velocity on the frequency in two-phase flow in conventional channels [3].

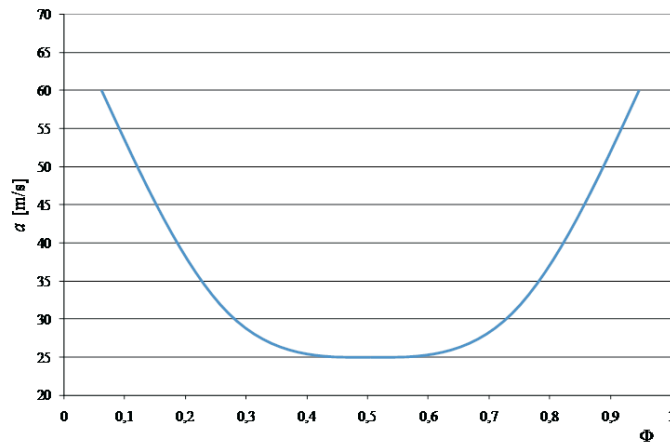


Figure 4. Dependence of the sound velocity on the void fraction [4].

that the velocity depends on the frequency of the disturbances. It must be emphasized that the void fraction has a substantial influence on the characteristics of this dependence. Figure 4 presents a typical diagram of the dependence of the sound velocity in a conventional channel on the void fraction, which has been determined in other papers by the authors

[1,3,30]. Therefore, there is a question as to how to determine the influence of void fraction Φ on the pressure signal propagation velocity v_p as the R134a refrigerant condenses in the pipe minichannels. Usually, the void fraction Φ is not measured directly but is determined from the correlations defined in the literature for a known steam quality x , for example, the correlations given by the author of paper [8]. In that paper, attention was also paid to the influence of the choice of the analytical correlation between the void fraction Φ and the characteristics of the condensation of the R134a refrigerant in minichannels subjected to periodic disturbances. The correlations due to following authors were considered: homogeneous fluid, Zivi, Rigot, Chisholm, Yashar *et al.*, and Premoli *et al.* The forms of these correlations are presented below:

- homogeneous model [8]:

$$\Phi_H = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right) S}, \quad (4)$$

where the value of slip $S = 1$;

- Zivi [32]:

$$\Phi = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right)^{\frac{2}{3}}}; \quad (5)$$

- Rigot [25]:

$$\Phi_H = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right) S}, \quad (6)$$

for $S = 2$;

- Chisholm [7]:

$$\Phi_H = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right) S}, \quad (7)$$

where: $S = \left(1 - x + \frac{x\rho_l}{\rho_g}\right)^{\frac{1}{2}}$;

- Yashar *et al.* [31]:

$$\Phi = (1 + F_t^{-1} + X)^{-0.321}, \quad (8)$$

where: $F_t = \left(\frac{x^3 G^2}{\rho_g^2 g d (1-x)}\right)^{0.5}$, $X = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1}$;

- Premoli *et al.* [23]:

$$\Phi_H = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right) S}, \quad (9)$$

$$\text{where: } S = 1 + K \left(\frac{Y}{1+CY} - CY\right)^{0.5}, \quad K = 1.578 + \text{Re}_1^{-0.19} \left(\frac{\rho_l}{\rho_g}\right)^{0.22},$$

$$Y = \frac{\beta'}{1-\beta'}, \quad C = 0.0273 \text{We}_l \text{Re}_l^{-0.51} \left(\frac{\rho_l}{\rho_g}\right)^{-0.08}, \quad \beta' = \frac{1}{1 + \left(\frac{1-x}{x}\right) \left(\frac{\rho_g}{\rho_l}\right)}.$$

Figures 5–6 present examples of experimentally measured dependences v_p for which the void fraction Φ was determined according to the correlations presented above (given the steam quality x obtained in the experiments) and for frequency $f = 0.25$ –5 Hz.

3 Conclusions

The present research determined the influence of the void fraction Φ on models of the condensation of R134a refrigerant in the presence of instabilities known as periodic hydrodynamic disturbances. In this study, the following correlations were analyzed: homogenous, Zivi, Rigot, Chisholm, Yashar *et al.* and Premoli *et al.* The results obtained were compared to the measured velocity of pressure instabilities during the condensation of R134a refrigerant in pipe minichannels with the following internal diameters: 0.64; 0.90; 1.40; 1.44; 1.92 and 3.30 mm. The following conclusions formulated analyzing the experimental results:

1. Generation of periodic dynamic disturbances during condensation of R134a refrigerant in pipe minichannels with diameters 0.64–3.30 mm significantly influences the characteristics of the condensation process.
2. The characteristics of the dependence of the pressure signal propagation velocity v_p on the void fraction Φ during the condensation of R134a refrigerant in pipe minichannels are similar to the characteristics in conventional channels.
3. The void fraction Φ distinctly influences on the pressure signal propagation velocity v_p . The experimental examinations of the condensation of R134a refrigerant in minichannels demonstrated that the experimental results most closely matched the calculations from the void fraction Φ when the homogeneous correlation was used.

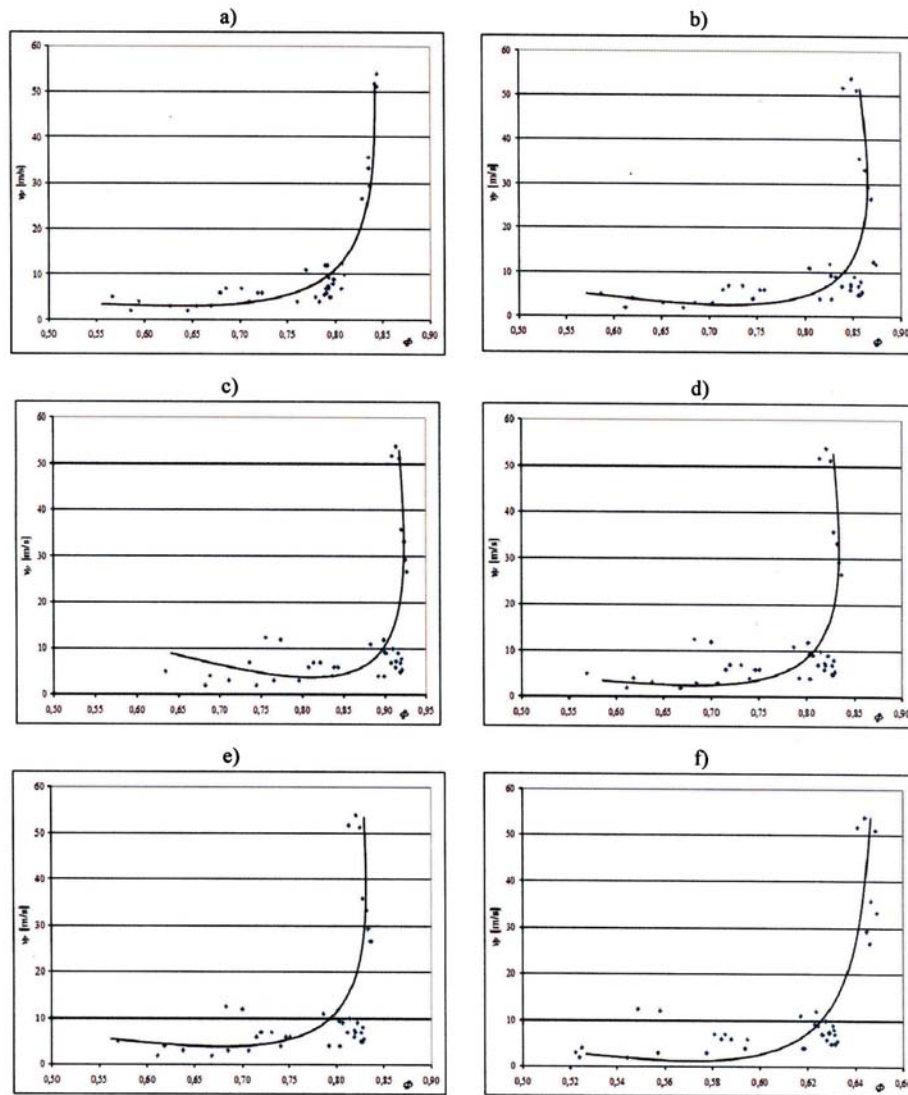


Figure 5. Results of experimental determinations of the function $v_p = f(\Phi)$ during the condensation of R134a refrigerant in pipe minichannels with internal diameter $d_w = 0.64$ mm subject to periodic instabilities. The void fraction was calculated using the following correlations: a) Zivi, b) Rigot, c) homogeneous, d) Chisholm, e) Yashar *et al.*, f) Premoli *et al.*

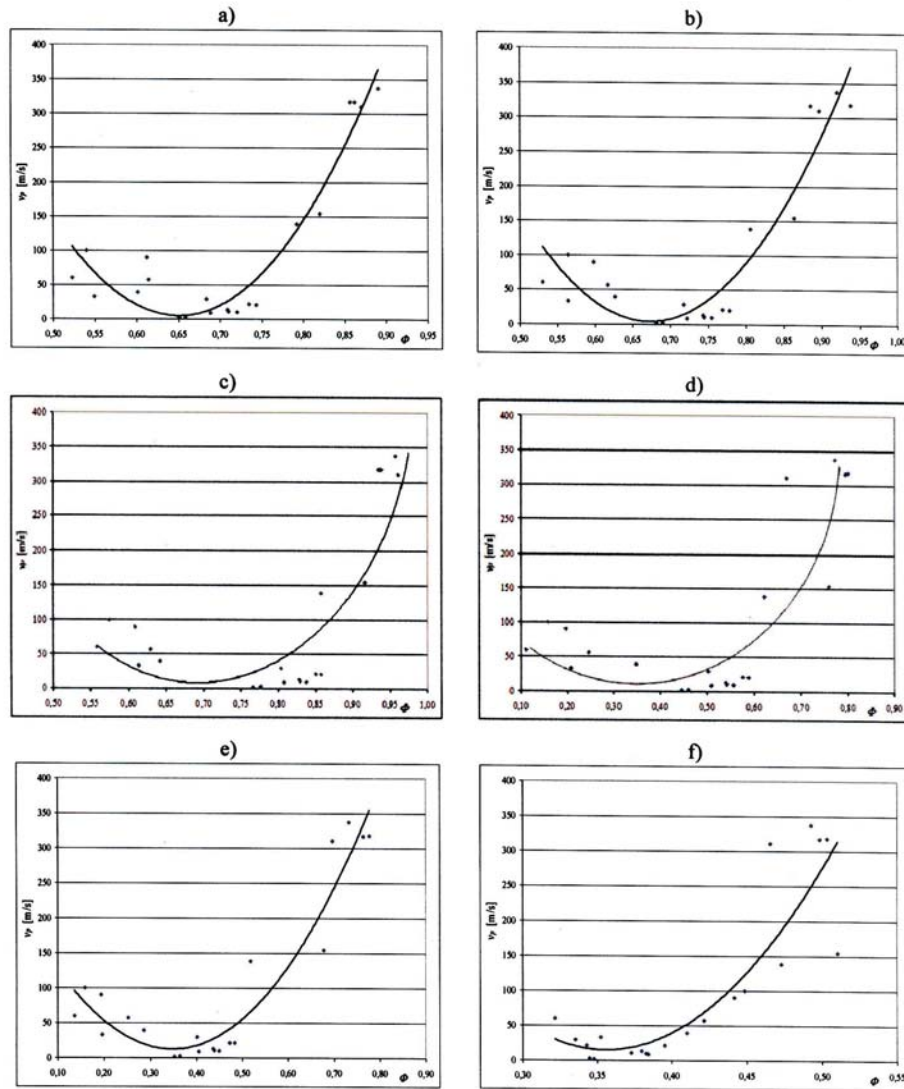


Figure 6. The results of experimental determinations of the function $v_p = f(\Phi)$ during the condensation of R134a refrigerant in pipe minichannels with internal diameter $d_w = 3.30$ mm, subject to periodic instabilities. The void fraction was calculated using the following correlations: a) Zivi, b) Rigot, c) homogeneous, d) Chisholm, e) Yashar *et al.*, f) Premoli *et al.*

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