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Analysis of propagation of disturbances in a two-phase refrigeration medium

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Abstract

A theoretical and experimental analysis of propagation of disturbances and determination of propagation velocity in a two-phase refrigeration medium has been made. During investigations on the experimental facility, a step change of the pressure in flow of a refrigerant R404A was induced. The introduced disturbance propagated with a finite velocity depending on the parameters of the medium and, more markedly, on the void fraction. The obtained experimental data were compared with results of calculations based on formulas of other investigators.

Keywords: Condensation, Heat transfer, Instabilities, Wave phenomena, external disturbances

Nomenclature

c	–	speed of sound, m/s
d	–	pipe inner diameter, m
L	–	coil tube length, m
p	–	pressure, MPa
Δp	–	pressure drop, MPa
q	–	heat flux density, W/m^2
T	–	temperature, K
t	–	time, s
$(w\rho)$	–	mass flux density, kg/m^{2}s
v	–	wave velocity, m/s
x	–	dryness fraction

Greek symbols

φ	–	void fraction
ρ	–	density, kg/m^3

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Subscripts

p – pressure
s – saturation
T – temperature

Superscripts

$'$ – liquid
$''$ – vapour

1 Introduction

The two-phase system, that is a one- or multi-component liquid-gas system, is a collection of particles of two states of aggregation separated by an interface. The character of interaction between the phases as well as the velocity of propagation of internal or external disturbances depends on the internal structure of the two-phase system. This is clear, for example, from propagation of a sound wave in the adiabatic two-phase system. The speed of sound is determined mainly by the void fraction φ and pressure of the two-phase mixture (Figs. 1 and 2). It follows from the presented graphs that the speed of sound in the two-phase system increases with the increasing pressure. This tendency remains valid until a certain value of pressure (whose value is dependent on the void fraction). Then at sufficiently high pressures the speed of sound remains constant and equals approximately 1300 m/s [12].

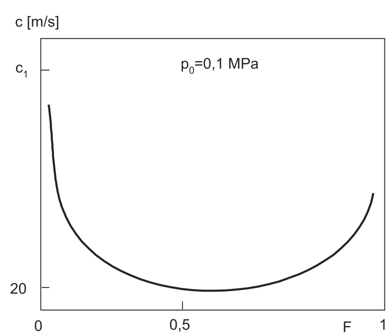


Figure 1. Dependence of the sound velocity c on the mean void fraction φ of the two-phase system [12].

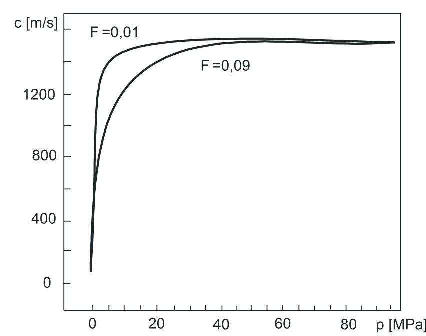


Figure 2. Dependence of the sound velocity c on the amplitude of pressure at a constant void fraction φ [12].

The propagation of a disturbance wave in the two-phase mixture whose thermal parameters are those of the saturation line leads to periodical changes of local values of pressure, which in turn results in a continuous phase change processes. At the interface, the process of condensation occurs where the pressure rises, the process of evaporation takes place during a pressure decrease. Local values of the parameters of the two-phase system such as the saturation pressure p_s, saturation temperature T_s, density ρ, dryness fraction (quality) x and void fraction φ undergo variations. These phenomena lead to a "damping effect" associated with the dissipation of energy and change of the disturbance propagation velocity [1,11,14,15].

In a non-equilibrium two-phase system a disturbance signal undergoes evolution. Two-phase flow has dispersive wave properties pronounced in a dependence of the velocity of propagation of small disturbances on their frequency [2,4,10]. Experimental investigations conducted for one-component and two-component two-phase flows show that subcritical two-phase flows in *de Laval* nozzles are possible for the pressure ratio of 0.2 and below. It should be underlined that a deep understanding of the mechanism of propagation of disturbances in the two-phase medium is important for stable operation of energy devices. The determination of disturbance propagation velocities is crucial for the description of operation of heat and refrigeration installations working under conditions of automatic control as well as for preventing breakdowns or reducing consequences of their occurrence [3,7,8,12].

2 Propagation of disturbances in a two-phase system

The velocity of propagation of disturbances in the two-phase medium depends on the physical properties of the mixture, the content of the liquid and gas phase described by the void fraction φ as well as on the two-phase structure, which is especially important in channel flows. A disturbance generated by a pressure change propagates within the two-phase system in the form of a pressure wave accompanied by a wave of change of void fraction and a temperature wave [5,6]. A change of mass flux density in the channel can also occur. These disturbances propagate with a finite velocity. The pressure wave propagation velocity is equal to the speed of sound in the two-phase system. The speed of sound in the dispersive fluid flow can be determined based on relations obtained as a solution of the assumed theoretical model. For the one-fluid model, assuming a homogeneous flow of the mixture, the following relation of *Wood* [12] can be used

$$c = \frac{\dfrac{1}{\sqrt{\varphi \cdot \rho'' + (1-\varphi)\cdot \rho'}}}{\sqrt{\dfrac{\varphi}{\rho'' \cdot c''^2} + \dfrac{1-\varphi}{\rho' \cdot c'^2}}} \quad . \tag{1}$$

In the case of the two-fluid model, the *Nguyens* relation is valid [13]

$$c = \frac{\dfrac{1}{\varphi\sqrt{\rho''} + (1-\varphi)\sqrt{\rho'}}}{\sqrt{\dfrac{\varphi}{\rho''\cdot c''^2} + \dfrac{1-\varphi}{\rho'\cdot c'^2}}} \quad , \tag{2}$$

where c is the speed of sound in the two-phase system determined for the homogeneous flow of a mixture.

Results of experimental and theoretical analysis of propagation of disturbances through a tubular channel in the form of a pressure wave and a void fraction wave are presented in the work [9]. The investigations were conducted for the case of flow of a mixture of water and air in a tubular channel of length $L = 30$ m and inner diameter $d = 60$ mm. Values of pressure p and void fraction φ were measured in three sections located along the channel. With the help of a shock tube, a pressure impulse was induced, which then propagated along the channel. The measurements were conducted for several types of two-phase flow structures, including annular, stratified, cork, droplet or bubbly flow. Sample results of measurements of pressure change during bubbly flow and results of measurements of the void fraction in the channel after an impulse disturbance of the pressure are presented in Figs. 3 and 4, respectively. The change of void fraction in the course of time is a result of different velocities of the pressure wave in the liquid and gas

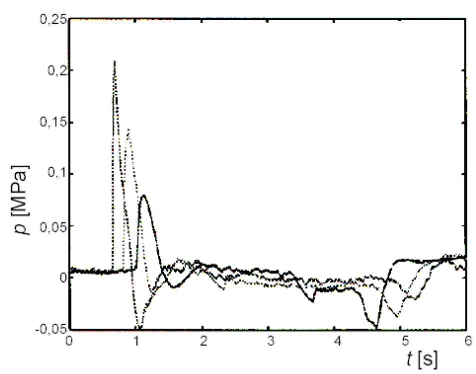


Figure 3. Pressure transients after an impulse disturbance in the channel – bubble flow; $\varphi = 0.22$ [9].

phase. This leads to additional wave effects at the interface resulting from stresses that occur there. Locally appear "vapour corks" or the content of the gas phase in the flowing liquid is decreased. This phenomenon is especially characteristics for stratified flow. In this case the pressure wave occurring in the gas phase (in the upper part of the horizontal channel) propagates considerably faster than in

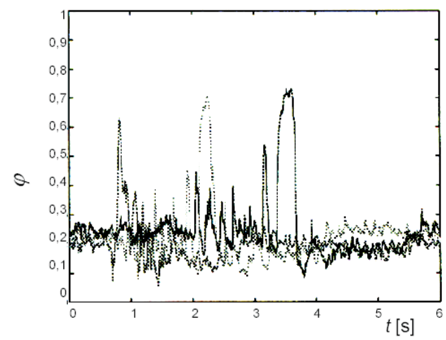


Figure 4. Void fraction transients after a pressure impulse in the channel – bubble flow; $\varphi = 0.23$ [9].

the two-phase mixture (in the lower part of the channel)). Results of theoretical calculations (based on relations 1 and 2) and experimental data published in the work [9], gathered in the form of a dependence of the pressure impulse propagation velocity v_p on the void fraction φ and two-phase flow structure is illustrated in Fig. 5. The effect of the void fraction φ on the value of the velocity v_p is relatively easy to read. To a lesser extent the velocity v_p can be influenced by the type of two-phase flow. The presented pictures also exhibit considerably large discrepancies between the results of experimental investigations and theoretical calculations. The application of the homogeneous model (1) yields the discrepancies even as large as 100%. A better agreement between experimental and theoretical results can be obtained if the two-fluid model (2) is applied. The discrepancies are typically about 30%, however can also reach 50%.

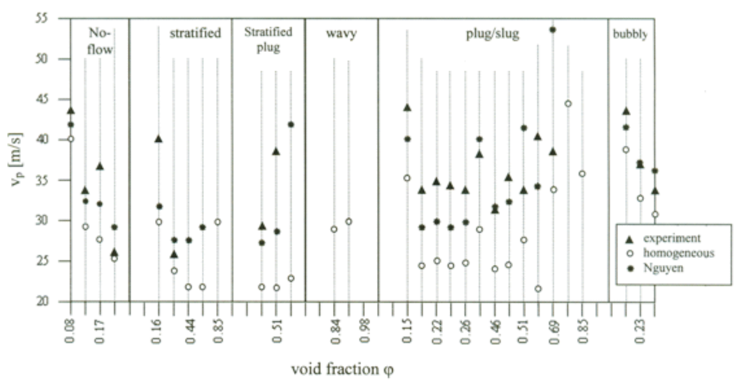


Figure 5. The pressure signal propagation velocity in the two-phase system. Comparison of experimental data and results of theoretical calculations (based on Eqs. 1 and 2) [9].

3 Experimental facility

Experimental investigations of the *condensation process* were made on a special design model condenser. The model condenser was built in the form of tube-in-tube heat exchange sections of outer diameter ϕ 35/31 mm and inner diameter ϕ 15/13 mm. Horizontal sections of straight tubes of length 1000 mm were connected by means of elbows forming a coil tube, which is a typical element of condensers used in refrigeration installations. The total length of the coil tube was $L = 15$ m. The vapour of the refrigerant was condensed during flow through a copper tube of inner diameter $d = 13$ mm, when cooled by water flowing in the inter-tube space. The condenser was insulated from outside by a polyurethane layer. The construction of the condenser facilitated the calculation of energy balances for each horizontal tube section and the coil tube as a whole. This enabled the identification of the process of heat exchange along the coil tube and determination of different heat transfer zones, including the vapour superheat zone, condensation zone and condensate subcooling zone. It was also possible to determine mean and local values of heat transfer coefficient, especially for the condensation zone [5, 7]. A schematic of the model condenser is presented in Fig. 6.

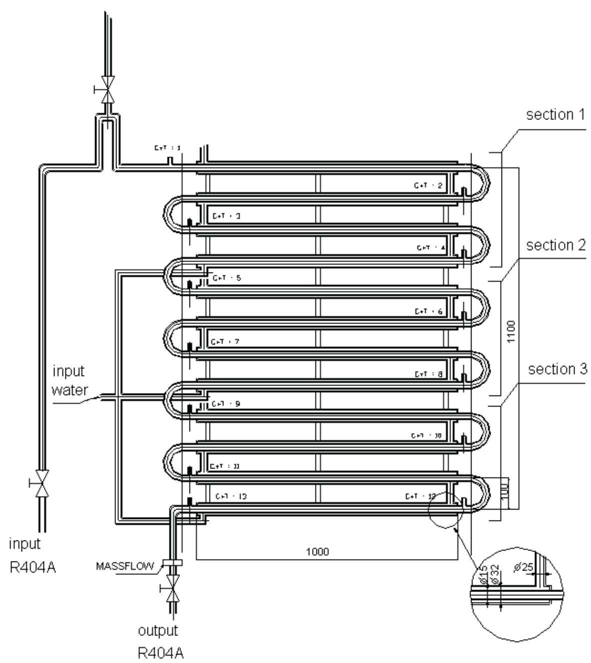


Figure 6. Schematic of the model condenser.

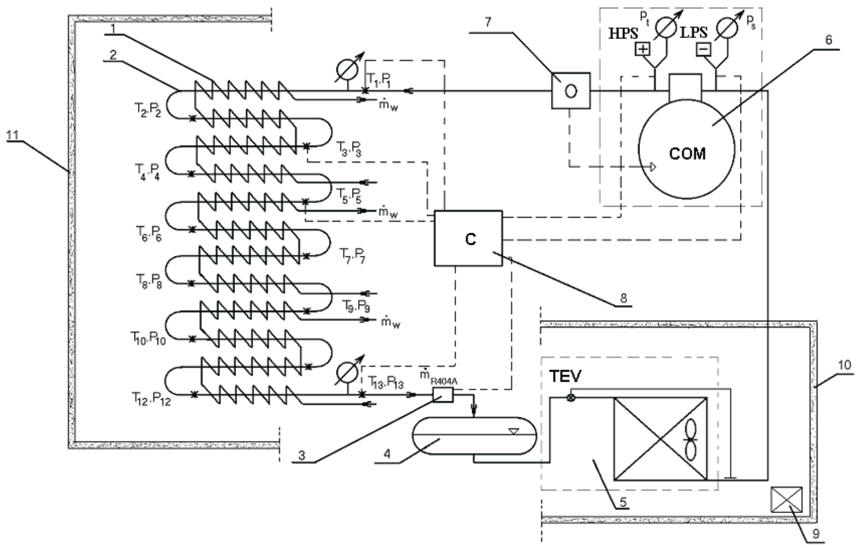
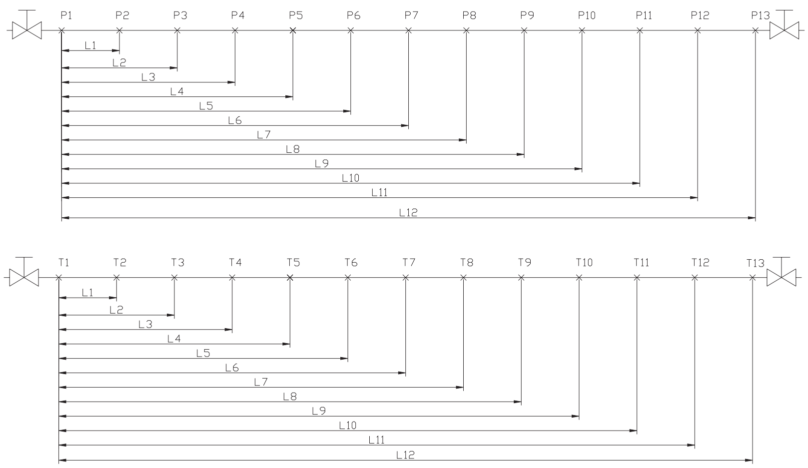


Figure 7. Schematic of the experimental facility 1 – condenser section, 2 – tubular elbow, 3 – refrigerant mass flow measurement, 4 – R404A liquid vessel, 5 – air fan cooler, 6 – (COM) compressor unit of type 4P-10.2Y produced by Bitzer, 7 – oil separator, 8 – data acquisition computer system, 9 – element of the heat load control system in the refrigeration chamber, 10 – isolated refrigeration chamber, 11 – measurement section shield, T,P – sets of sensors for temperature and pressure measurements in selected nodes of the refrigerant and water system, HPS – high pressure control system, LPS – low pressure control system, TEV – thermostatic expansion valve, Pt – pumping pressure manometer, Ps – suction pressure manometer, $\dot{m}$ – refrigerant mass flow rate, $\dot{m}_w$ – water mass flow rate.

A schematic of the experimental facility, where the investigations were conducted is presented in Fig. 7. The model condenser was installed in a one-stage compressor refrigeration unit operating with R404A as a refrigeration medium. A change of the heat load of the condenser was obtained by changing the load of the isolated refrigeration chamber 10, where the air fan cooler (with appropriate instrumentation) and additional heating elements were also placed. The vapour of the refrigerant was sucked by the compressor and, after compression, fed to the condenser and further to the liquid vessel 4. In order to carry out detailed measurements of the refrigerant and coolant parameters, the investigated refrigeration unit was equipped with a measuring system. The coil tube was equipped with 12 sensors for pressure measurements and 12 sensors for temperature measurements installed along the coil tube (Fig. 8). Temperature measurements were made using thermoelectric sensors of type K of thermoelectrode diameter ϕ0.2 mm. Tensometric sensors and control spring manometers of class 0.1 were used for pressure measurements. Prior to the measurements all pressure and temperature sensors were calibrated and individual characteristics of each sensor were made.

A computer system of measurement data acquisition 8 with computer interfaces was used. The system was also equipped with an electronic flow meter *Massflo* produced by *Danfoss* for measurement of refrigerant flow. The flow rate of the refrigerant was also checked by an independent system of calibrated vessels. The mass flow rate of water was measured by the electronic flow meter, too. The flow rate was controlled by a calibrated laboratory rotameter. Measurements of temperature and pressure were accurate to $\pm 0.02^{\circ}$C and ± 10 Pa, respectively, whereas the error margin for measurements of heat flux density q and mass flux density $(w\rho)$ was estimated as ± 6 %.



Lp	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
[m]	1.25	2.5	3.75	5	6.25	7.5	8.75	10	11.25	12.5	13.75	15

Figure 8. A schematic of the set-up of measuring sensors for temperature (T) and pressure (P) measurements along the tube coil of the model condenser (as uncoiled).

4 Experimental investigations

The authors conducted experimental investigations of propagation of a disturbance in the form of a pressure change signal during condensation of refrigerant R404A in a tubular channel of a refrigeration heat exchanger. An impulse change of pressure at the inlet to the coil tube was induced using a cut-off valve located at the inlet to the condenser. A pressure decrease was achieved while decreasing the valve opening, whereas the pressure was increased while increasing the valve opening. The induced pressure change signal Δp propagated in the condensing refrigerant along the coil tube with a velocity v_p. During measurements, values of pressure and temperature along the coil tube in the course of time were recorded. Based on the obtained results of measurements it was found that the external disturbance leading to a change of pressure by Δp propagated along the coil tube in the form of a pressure wave followed by a temperature wave. The pressure wave propagated with a large velocity of the order of $v_p = 50 \div 300$ m/s, whereas the temperature wave had the velocity $v_T = 0.3 \div 0.6$ m/s. Large differences in propagation velocities of pressure and temperature waves arise from different mechanisms of their propagation. The pressure wave propagation velocity corresponds to the speed of sound in the two-phase system. Its value is determined (mainly) by the void fraction φ of the refrigerant in the channel, which is illustrated in Fig. 1. The lowest value of the pressure wave propagation velocity refers to the value of void fraction approximately $\varphi = 0.5$. The value of the temperature wave propagation velocity is strictly associated with the velocity of propagation of the pressure change signal and change of the mass flux of the flowing two-phase mixture. On the one hand, the temperature of the two-phase mixture is a function of the local pressure in the channel, on the other hand, it is affected by heat inertia of the system while tending to a new state of equilibrium. Sample changes of pressure of the refrigeration medium along the coil tube during propagation of the wave of pressure decrease or increase in the model heat exchanger are presented in Fig. 9 and 10.

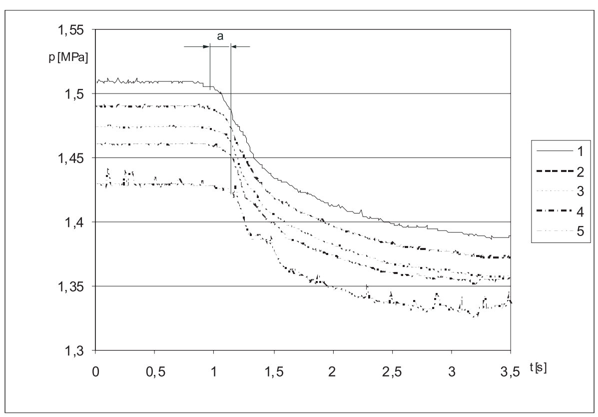


Figure 9. Experimental pressure transients for refrigerant R404A under conditions of a drop of condensation pressure in the heat exchanger; $(w\rho) = 205$ kg/m^{2}s, $q = 13.9$ kW/m^2, $v_p = 83.4$ m/s; subsequent curves refer to pressure sensors: 1 – P1, 2 – P3, 3 – P6, 4 – P9, 5 – P12.

The distribution of pressure of the refrigerant R404A along the coil tube

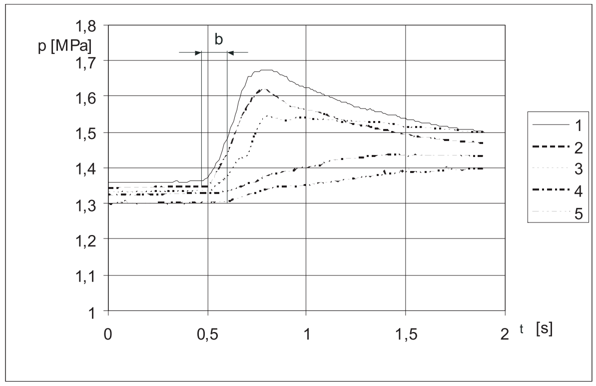


Figure 10. Experimental pressure transients for refrigerant R404A under conditions of a rise of condensation pressure in the heat exchanger; $(w\rho) = 218$ kg/m^{2}s, $q = 11.4$ kW/m^2, $v_p = 151.4$ m/s; subsequent curves refer to pressure sensors: 1 – P1, 2 – P3, 3 – P6, 4 – P9, 5 – P12

recorded at several instants of time after initiation of the disturbance is illustrated in Fig. 11 and 12. Changes of pressure along the coil tube depend mainly on the mass flux density and void fraction of the two-phase system, however the most important is the pressure value at the inlet to the channel with the condensing refrigerant.

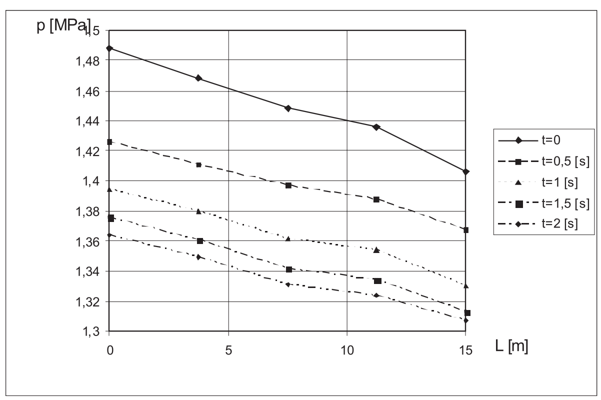


Figure 11. Distribution of pressure of refrigerant R404A along the coil tube in the course of time after a pressure drop: $(w\rho) = 245$ kg/m^{2}s, $q = 17.1$ kW/m^2, $v_p = 139.8$ m/s.

The dependence of the propagation velocity v_p on the pressure change signal Δp in flow of a refrigerant in a coil tube is illustrated in Fig. 13. The propagation of the pressure signal Δp was followed by the condensation front, propagating with a significantly lower velocity v_T, which is presented in Fig. 14. The measurement

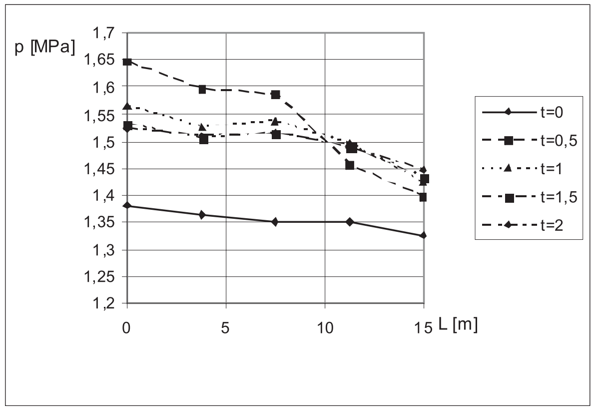


Figure 12. Distribution of pressure of refrigerant R404A along the coil tube in the course of time after a pressure rise: $(w\rho) = 245$ kg/m^{2}s, $q = 17.1$ kW/m^2, $v_p = 136.6$ m/s.

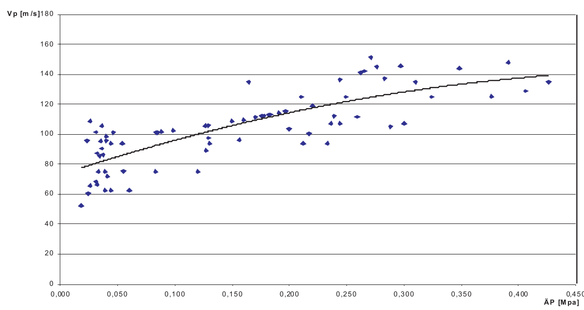


Figure 13. Dependence of velocity v_p of the displacement of the pressure change signal from the amount of the pressure change impulse Δp in the conditions of the development of condensation in the flow of R404A refrigerant in the coil tube.

results show that with the increasing value of Δp the disturbance propagation velocity also increases. In the investigated range of $\Delta p = 0-0.5$ MPa, the velocity v_p changed between $v_p = 70 - 140$ m/s. In Fig. 15, the acquired measured data are compared with results of theoretical investigations obtained with the help of relations (1) and (2). It is found from the comparison that for the same parameters of the two-phase system, values of the pressure wave propagation velocity obtained from the calculations based on the relation (2) are larger than those of (1). In a least favourable case (that is for $\varphi = 0.5$) the discrepancies are about 20%. Also the relation (2) describes in a better way the results of experimental investigations and it is recommended for the determination of disturbance propagation in the condensing flow of the refrigerant through a coil tube.

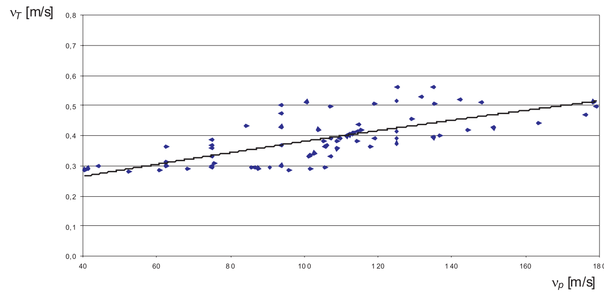


Figure 14. Comparison of the dependence of temperature wave propagation velocity v_T on the pressure impulse propagation velocity v_p during development of condensation in the coil tube.

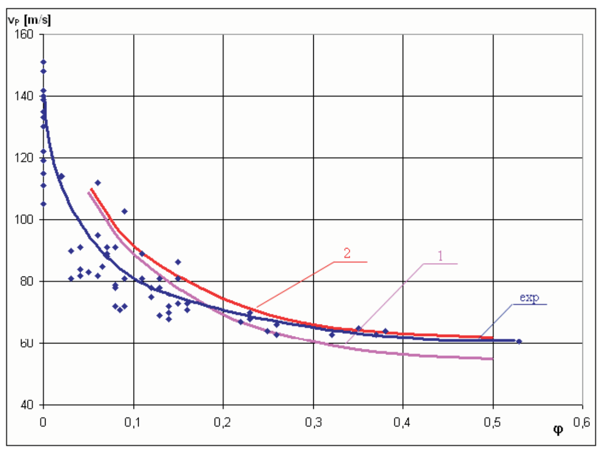


Figure 15. Dependence of velocity v_p of the displacement of the pressure change signal from the void fraction φ; $(w\rho) = 250$ kg/m^{2}s, $q = 12$ kW/m^2, $p = 1.4$ MPa.

5 Conclusions

1. The experimental investigations confirm the wave character of propagation of disturbances in the two-phase system. Signals of induced disturbances propagate in energy installations with a finite velocity. One can distinguish the pressure wave propagation velocity v_p and temperature wave propagation velocity v_t. Values of these velocities depend on the parameters of the two-phase system.

2. A unit impulse disturbance was followed by the propagation of a pressure wave with the velocity v_p followed by a change of the medium and channel wall temperature. Each time, the propagation of a temperature wave with the velocity v_t ($v_T \neq v_p$) was observed.

3. The results of experimental investigations are relatively well described by the two-fluid model of Nguyens. This model is recommended for determination of the disturbance propagation velocity in the condensing flow of the refrigeration medium through a coil tube.

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