archives
of thermodynamics
Vol. **44**(2023), No. 1, 121–137
DOI: 10.24425/ather.2023.145880

Modeling the phenomena accompanying the condensation of environmentally friendly refrigerants in mini-channels

WALDEMAR KUCZYŃSKI*

Koszalin University of Technology, Faculty of Mechanical Engineering, Department of Power Engineering, Racławicka 15-17, 75-625 Koszalin, Poland

Abstract This paper presents the results of an experimental study and mathematical modeling of the effect of dynamic instabilities on the condensation phase transformation of the refrigerants homogeneous R134a and its replacement in the form of isomers R1234yf and R1234ze and R404A or R507 and R448A in pipe mini-channels. In the case of homogeneous chlorofluorocarbons (CFCs), it is the 1234 isomers that are envisioned as substitutes for the withdrawn ones with high ozone depletion potential and global warming potential. For zeotropic and azeotropic mixtures, for example, these are R507 or R448A. The paper presents a dimensional analysis procedure based on the Buckingham Π theorem to develop a regression velocity model of pressure dynamic instabilities. The experimental part of the work was carried out with the use of tubular mini-channels with internal diameter 1.40–3.3 mm.

Keywords: Refrigerants; Condensation; Mini-channels

1 Introduction

In the many papers, the possibility of using computational models developed to describe the impact of dynamic instabilities on the process of condensation of refrigerants in pipe mini-channels is demonstrated [1, 4, 9, 10,

*Corresponding Author. Email: waldemar.kuczynski@tu.koszalin.pl

13, 18]. These methods refer to the computational determination of the velocity of displacement of pressure instabilities, and the velocity of the liquefaction front.

It should be noted that in the literature there is a lack of publications describing dynamic instabilities with unitary characteristics and, in particular, a lack of computational models. Filling this information gap are the author's models presented in this paper. They concern the modeling of the propagation of pressure instabilities and the movement of liquefaction front, resulting from non-stable interactions of unitary nature [17]. The given solution can be applied to the phase transformation of refrigerant liquefaction implemented in mini-channels [3,16,20,26]. A regression function was used to describe the velocity of the displacement of the pressure change signal and the temperature change signal. It describes the dependence of the expected value of a variable (in this case, the magnitudes of the velocity of displacement of pressure instabilities and the velocity of the liquefaction front) on the explanatory variables Buckingham Π theorem, assuming that the number of dimensionless modules is equal to the number of independent physical parameters, minus the number of basic dimensions [5,6,8]. The presented method of determining dimensionless numbers, describing the speed of propagation of instability and the unknowns occurring in the regression equations, is included, as constant quantities and exponents of powers.

The magnitude of the velocity of the movement of the pressure change signal caused by instabilities of a unitary dynamic nature (velocity of movement of pressure instabilities) was functionally dependent on the following parameters:

$$v_p = f(\Delta p,\, p_o,\, \upsilon,\, d,\, w), \tag{1}$$

where: Δp – amplitude of condensing pressure oscillations during disturbances, p_o – average condensing pressure of the refrigerant, υ – kinematic viscosity coefficient of the two-phase mixture, d – internal diameter of the mini-channel, w – average velocity of the two-phase refrigerant mixture.

Equation (1) shows that the speed of movement of unit dynamic instabilities depends on the amplitude and frequency of their generation and the physical properties of the refrigerant. The magnitude of the amplitude of pressure oscillations (Δp) depends, in turn, on the step (unit) change in this value. In the case under consideration, there is a sudden disappearance or development of the condensation phase transformation process, caused by the sudden closure (or opening) of the shut-off valve on the refrigerant supply to the pipe mini-channel.

The primary quantity affecting the generation of dynamic instabilities, both pressure and temperature, is the mass flow rate of the refrigerant. Instabilities of this type are associated with mass flux density disturbances [7].

In the case of dynamic instabilities of the mass flow rate ($\dot{m}$) of the refrigerant, there is an impulsive (one-time) change in this quantity. The velocity of the two-phase refrigerant mixture in this case is determined by the relation

$$\dot{m}_{\text{mix}} = w\rho_{\text{TFP}}A \quad \Rightarrow \quad w = \frac{\dot{m}_{\text{dist}}}{\rho_{\text{TFP}}A}\,, \tag{2}$$

where: A – cross-sectional area of the mini-channel, ρ_{TFP} – density of the two-phase mixture is determined from the relation

$$\rho_{\text{TFP}} = \frac{\rho_L\rho_G}{\rho_G + x\left(\rho_L - \rho_G\right)}\,, \tag{3}$$

where the subscripts G and L stand for gas and liquid, respectively. The vapor quality (x) of the refrigerant in the sections of the mini-channel was calculated according to publications on the subject [15, 21].

Performing the procedures related to the application of dimensional analysis to relation (1) led to the dimensionless propagation velocity of unitary pressure instabilities:

$$v_p^+ = C\,\text{Re}_{\text{TPF}}^a\left(\Delta p^+\right)^b, \tag{4}$$

where: a, b – exponents; C – constant; Δp^+ – dimensionless pressure drop, Re_{TPF} – Reynolds number for two-phase flow.

The dimensionless propagation velocity of pressure instabilities was determined by the ratio of the propagation (v_p) of the displacement of the pressure change signal to the average velocity in the two-phase mixture (w), $\left(v_p^+ = \dfrac{v_p}{w}\right)$ and the dimensionless pressure drop was defined by the ratio of the amplitude (Δp) of pressure to the pressure (p_o) of condensing refrigerant $\left(\Delta_p^+ = \dfrac{\Delta p}{p_o}\right)$. The Reynolds number for two-phase flow in a mini-channel can, with the internal diameter d, be expressed as

$$\text{Re}_{\text{TPF}} = \frac{w\rho_{\text{TPF}}d}{\eta}\,,$$

where η is the dynamic viscosity.

Equation (4) reduces to the following linear form:

$$\log v_p^+ = \log C + a\log \text{Re}_{\text{TPF}} + b\log \Delta p^+. \tag{5}$$

The value of the constant C and the exponents a and b were calculated using a nonlinear regression model. The method used the procedure of highest reliability, which is an alternative to the method of least squares. The standard deviation of the observed value from the predicted value was determined using the so-called loss function. Maximization of the credibility function (selection of appropriate parameters satisfying this condition) was performed using the quasi-Newton and symplex methods, which are standard calculation modules in the Statistica software package. Equilibrium calculus was carried out (for a given refrigerant) for an appropriate number of equations built on the basis of experimental results for the range of applied disturbances.

In an analogous way to the regression function for unit pressure instabilities, the values of the dimensionless velocity of propagation of the liquefaction front were determined relating to the movement of temperature instabilities:

$$v_T = f(\Delta T,\, T_o,\, \upsilon,\, d,\, w), \tag{6}$$

where ΔT is the temperature oscillation and T_o is the refrigerant condensation temperature. The application of dimensional analysis procedures made it possible to formulate the relationship for dimensionless velocity in the form of

$$v_T^+ = C\mathrm{Re}_{\mathrm{TPF}}^a \left(\Delta T^+\right)^b, \tag{7}$$

where ΔT^+ is the dimensionless temperature drop determined by the ratio of the amplitude of the temperature oscillation, to the magnitude of the refrigerant condensation temperature $\left(\Delta T^+ = \dfrac{\Delta T}{T_o}\right)$.

Relationship (7) was also reduced to linear form:

$$\log v_T^+ = \log C + a \log \mathrm{Re}_{\mathrm{TPF}} + b \log \Delta T^+. \tag{8}$$

Calculation of the constant C and the exponents a and b in Eq. (8) were performed according to the same calculation procedures as for the nonlinear regression model defined by relation (5).

The developed regression model was used to determine the propagation velocity of pressure and temperature instabilities occurring during the generation of unitary instabilities. The occurrence of physical phenomena of such instability character is associated with the process of rapid development or disappearance of refrigerant condensation, for example, in heat exchangers built of conventional channels, as well as mini-channels [14].

2 Methodology of experimental research

The realization of experimental studies was carried in accordance with for the identification of the effect of instabilities of a dynamic nature on the condensation of R404A and R134a refrigerants in mini-channels of pipes [12–14]. In the case of R507 and R448A refrigerants, the detailed parameters under which the tests were carried out were as follows:

- refrigerants – R404A, R507 and R448A;
- internal diameters $d = 3.3, 2.3, 1.9, 1.44$, and 1.40 mm;
- single channel configuration;
- refrigerant mass flux $G = 60$–316 kg/(m^2·s);
- refrigerant inlet pressure $p_{in} = 1.09$–7.5 MPa (saturation temperature in the range of 42.6–45.5°C.

Figure 1 shows a general view of the experimental station, while Fig. 2 shows a view of the measurement section, the schematic of which is presented in Fig. 3.

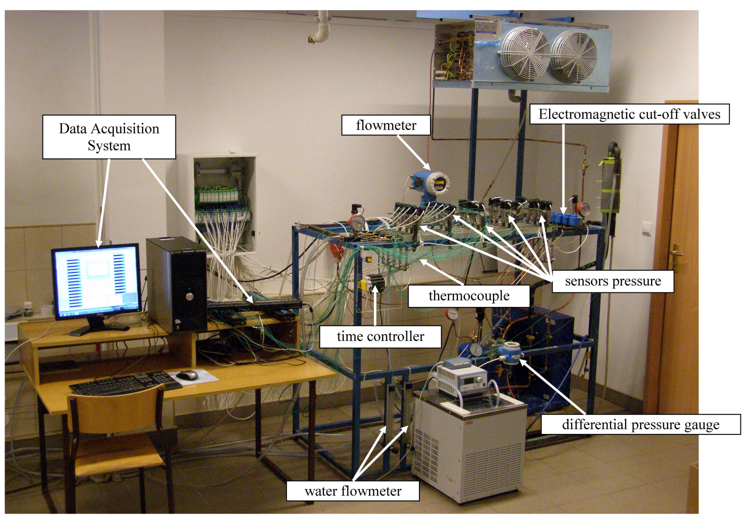

Figure 1: View of the test site [12–14].

Using electromagnetic cut-off valves (Fig. 1), instabilities of a dynamic nature were generated. The experiment was performed in a methodology that

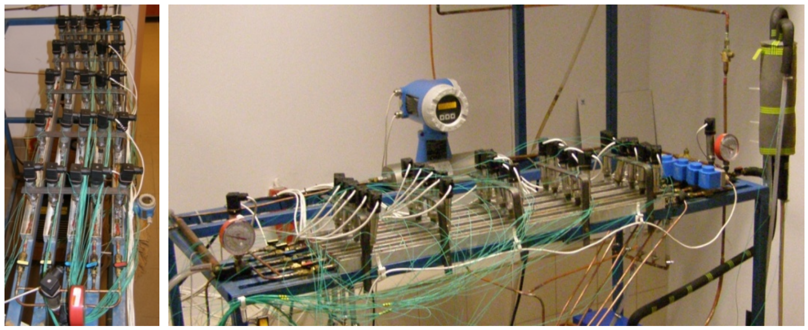

Figure 2: View of channels for studying heat transfer during refrigerant condensation in mini-channels of pipes with pressure and temperature sensors installed [12–14].

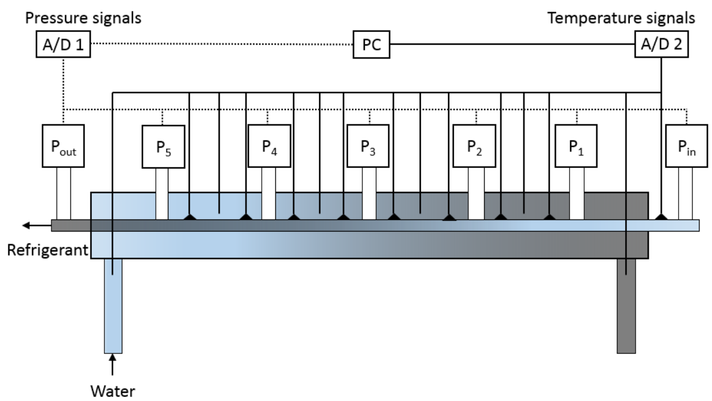

Figure 3: Schematic diagram of the measurement section [12–14].

allows identification of the development and disappearance of the condensation process of the studied refrigerants [2, 12, 19].

In order to achieve intensification of the liquefaction process, the method of increasing the mass flux by means of opening the supply valve with adjustable time (t) was used. On the other hand, the disappearance of the liquefaction process was obtained by abruptly closing the shut-off valve [12–14]. This allowed us to determine the minimum time at which the response of the system to the induced dynamic was noticeable is $t_o = 0.3$ s. Tests were carried out in the range of valve opening and closing times $t_o = 0.3$–3.5 s, using an increase or decrease in this time every 0.05 s in successive measurements. Figure 4 shows the results of the tests on the issue under consideration [12].

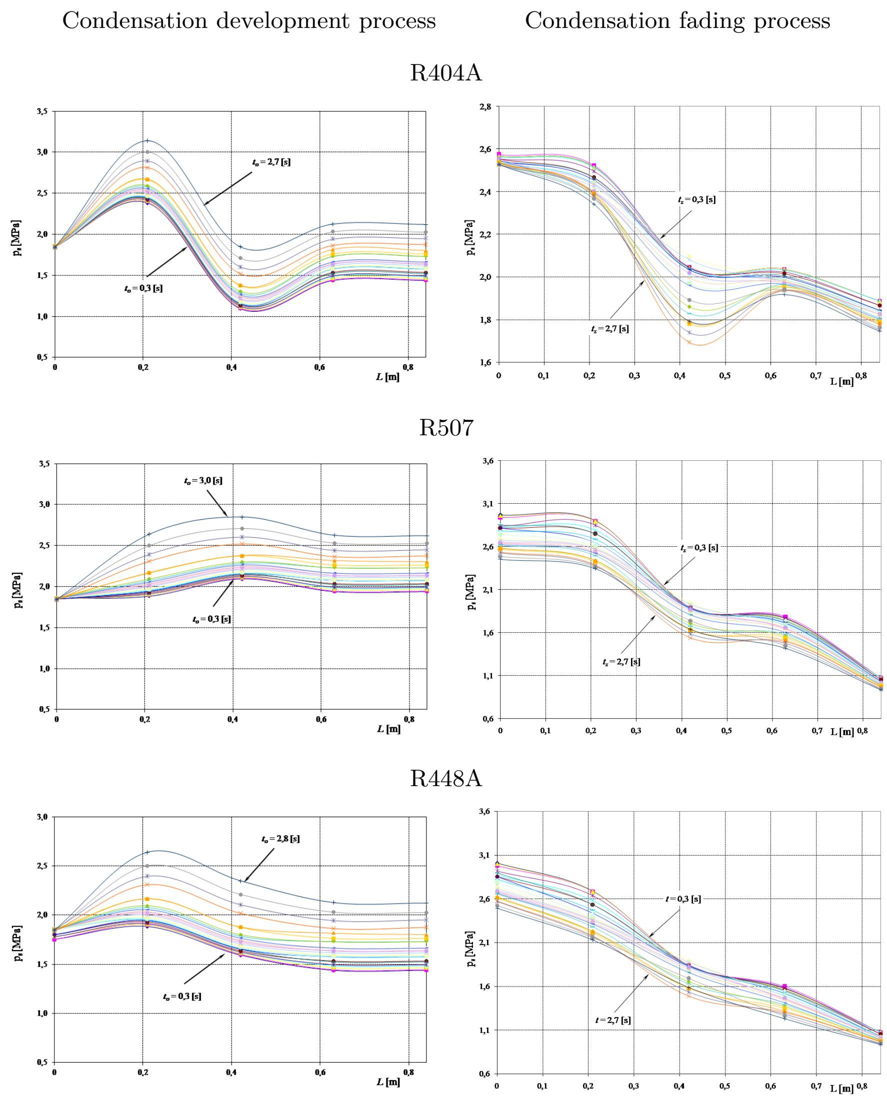

Figure 4: Distribution of pressure of the tested refrigerants depending on the time of closure (t_c) and opening (t_o) of the shut-off valve for the inner diameter of the tested mini-channel $d = 3.30$ m.

The result of the rapid influx of refrigerant vapors into the mini-channel is the displacement of the pressure change signal, which refers to the speed of propagation of pressure instabilities (v_p). Figure 5 illustrates the pressure change signal identified for R404A, R507A, and R448A mixtures.

Condensation development process Condensation fading process

R404A

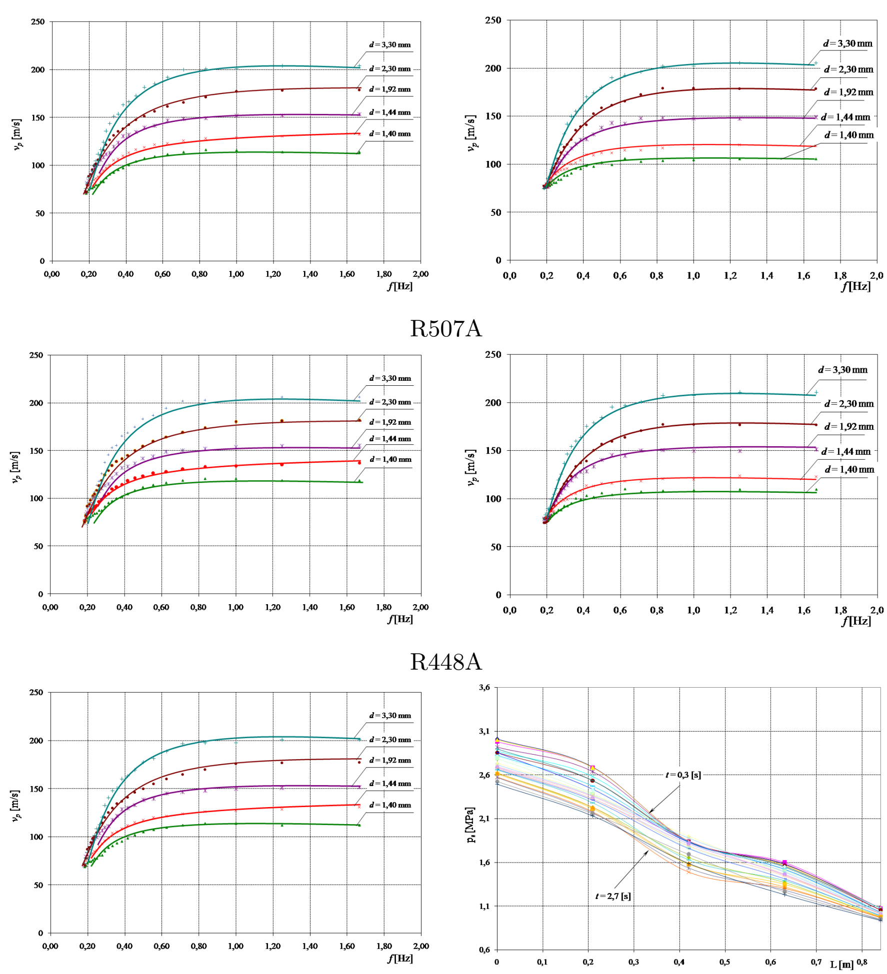

Figure 5: Speed of propagation pressure instabilities depending on the frequency of generated unit disturbances during liquefaction of tested refrigerants in mini channels of pipes.

The movement of pressure instabilities (v_p) is accompanied by the propagation of temperature instabilities (v_T). These are referred to the so-called the velocity of the condensation front (v_{FC}). It was observed that in the case of the development of the condensation process there is a decrease in the velocity of propagation of the condensation front, which moved in accordance with the direction of steam flow in the mini-channel. The decrease in velocity is due to an increase in the frequency of generated disturbances, which corresponds to a decrease in the opening time of the shut-off valve (Fig. 6). On the other hand, when the condensation process disappeared, the instability moved in the direction opposite to the incoming steam, re-

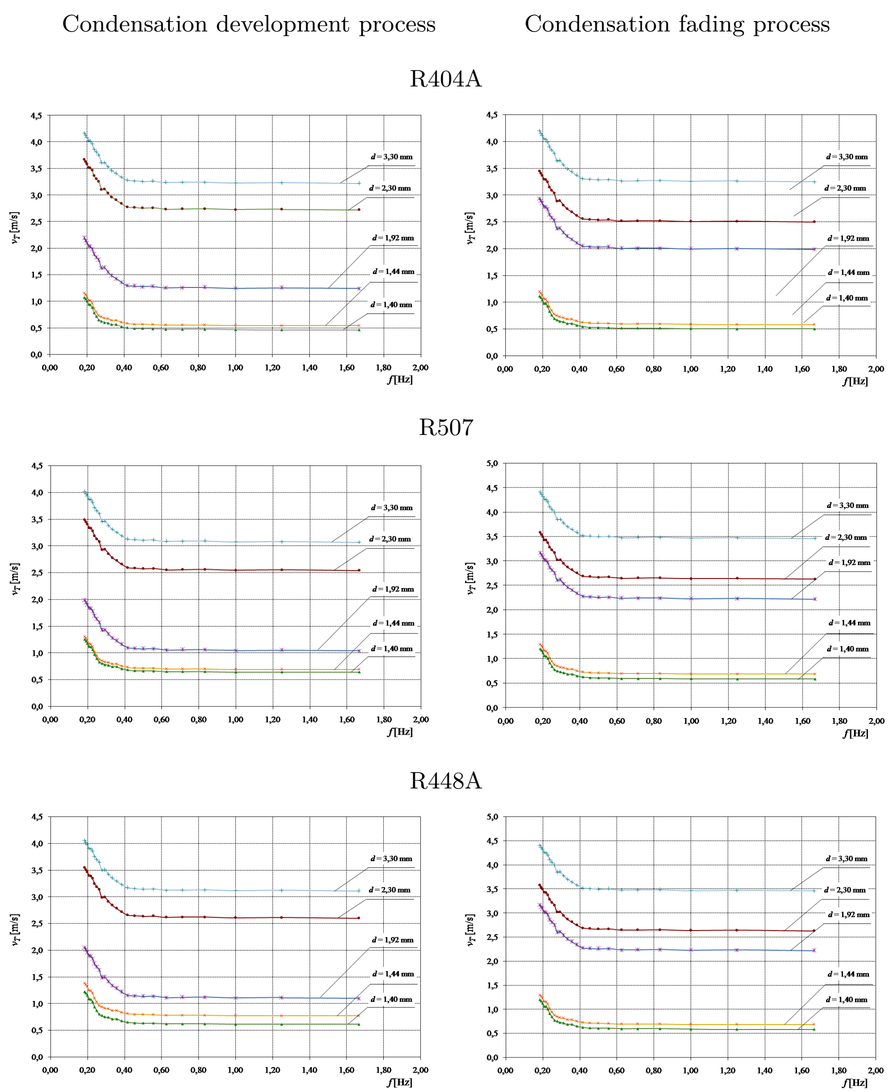

Figure 6: Dependence of the velocity of propagation of temperature instabilities on the frequency of generated unit instabilities for the studied refrigerants.

sulting in a reduction in the most effective area of condensation proper in terms of heat transfer [11, 22, 24, 26]. Figure 7 shows example distributions of pressure and temperature instability precipitates for R134A refrigerants and R1234ze and R1234yf isomers.

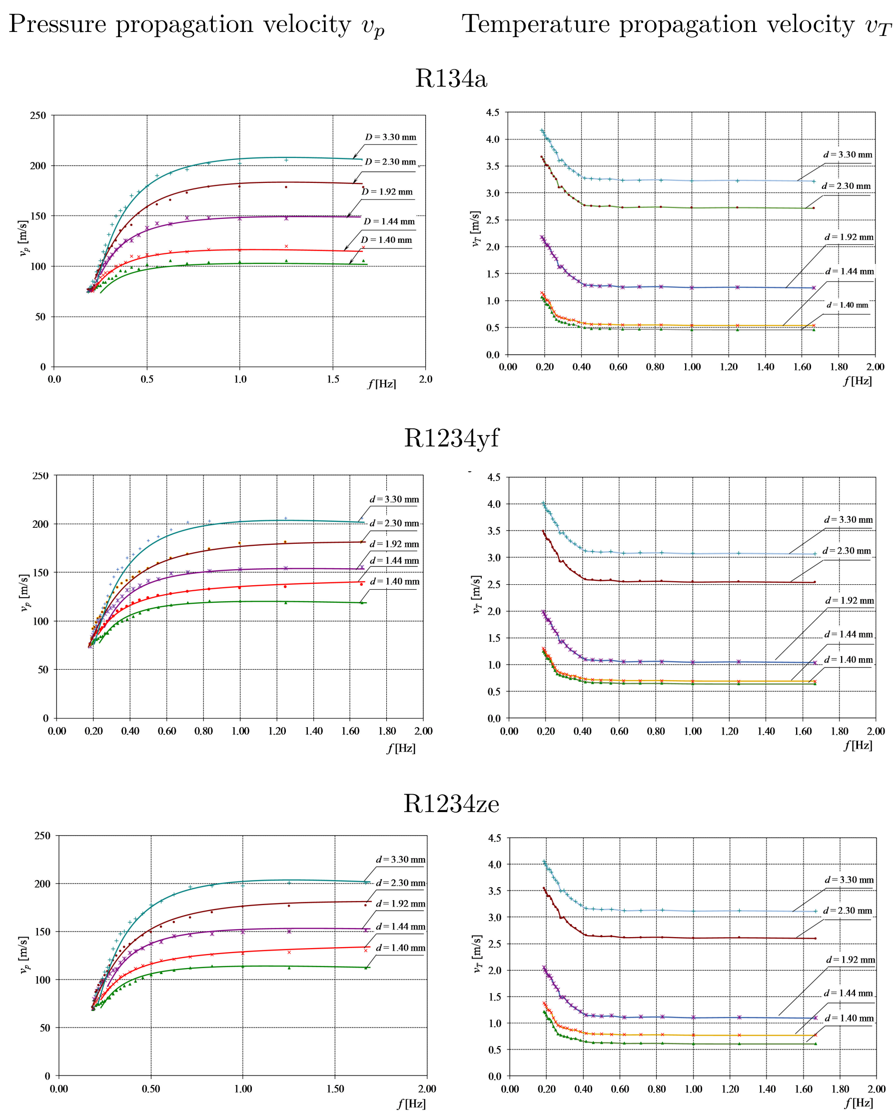

Figure 7: Propagation velocities of pressure (v_p) and temperature (v_T) instabilities as a function of the frequency of singular instabilities during condensation of tested refrigerants inside tubular mini-channels

3 Comparative comparison of computational models describing dynamic instabilities of unit liquefaction of pro-environmental agents in pipe mini-channels

For the studied refrigerants, the application of regression functions for the unit pressure and temperature instabilities occurring during the liquefaction process, the values of the unknowns C, a, and b were determined according to relations (4) and (7) with the corresponding variance from population (σ^2) and r-Pearson significance coefficients. Example calculation results for the studied refrigerants R448A and R1234yf are presented below.

In the case of the R448A refrigerant, for pressure instabilities occurring during the development of the liquefaction process, the following values were obtained: $C = 327.8$, $a = -0.52$, $b = -1.11$ with a variance of 96% and a significance factor $R = 0.91$. This allowed to, formulate the relationship in the following form:

$$v_p^+ = 327.8\text{Re}_{\text{TPF}}^{-0.52} \Delta p^{+^{-1.11}}. \tag{9}$$

The results of calculations according to Eq. (9) on the dimensionless velocity $v_{p\ \text{reg}}^+$ were compared with the results of experimental studies $v_{p\ \text{exp}}^+$, obtaining satisfactory agreement in the 25% range, as shown in Fig. 8.

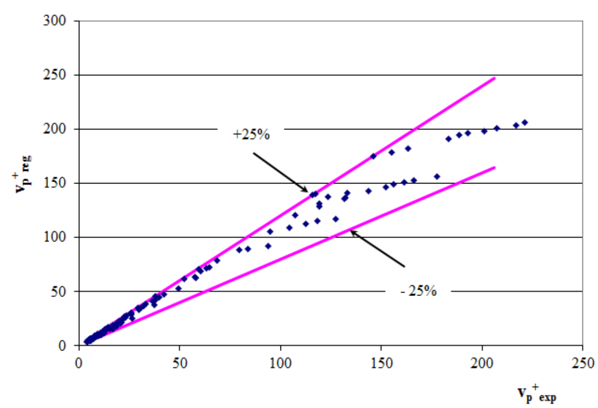

Figure 8: Dependence of dimensionless velocity ($v_{p\ \text{reg}}^+$) from the value obtained in experimental studies ($v_{p\ \text{exp}}^+$) for R448A refrigerant during the development of the condensation process.

Figure 9 presents the correlations obtained by means of applied statistical software for the parameters on which the regression model was based.

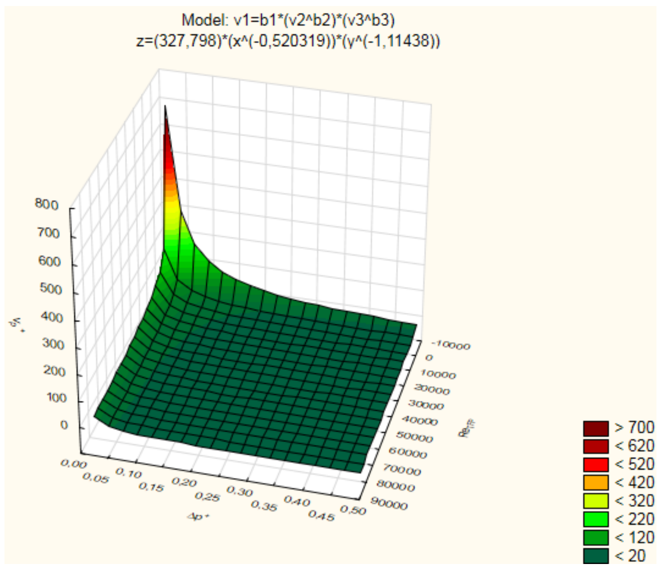

Figure 9: Interdependence of quantities forming the regression model (V_p^+, Δp^+, $\mathrm{Re_{TPF}}$, Eq. (9)) for R448A refrigerant during the development of the condensation process.

Analogous to the regression model of pressure instabilities, the values of the constants of the equation describing the dimensionless velocity speed of propagation of temperature instabilities were determined v_T^+ for the refrigerant R1234yf. The following values were obtained: $C = 0.00079$; $a = 0.34$; $b = -1.43$; with a variance of 98% and significance coefficient $R = 0.99$. Consequently, the following form of the regression function was obtained:

$$v_T^+ = 0.00079 \mathrm{Re}_{\mathrm{TPF}}^{0.34} \Delta T^{+^{-1.43}}. \tag{10}$$

Comparison of computational results obtained from relation (10) with experimental results showed a concordance of ±25% (Fig. 10). Figure 11 shows the correlations obtained by means of applied statistical software for the parameters on which the regression relationship was formulated for speed $v_{T\,\mathrm{reg}}^+$ in condensing refrigerant R1234yf.

Table 1 presents a summary of the quantities that form correlations, describing the dimensionless speed of propagation of pressure (v_p^+) and temperature (v_T^+) instabilities developed for refrigerants R134a, R1234yf,

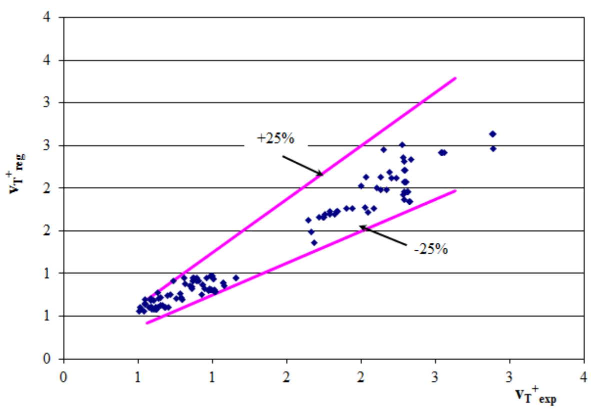

Figure 10: Dependence of dimensionless velocity $v^+_{T\,\mathrm{reg}}$ from the value obtained in experimental studies $v^+_{T\,\mathrm{exp}}$ for the refrigerant R1234yf, during the development of the condensation process.

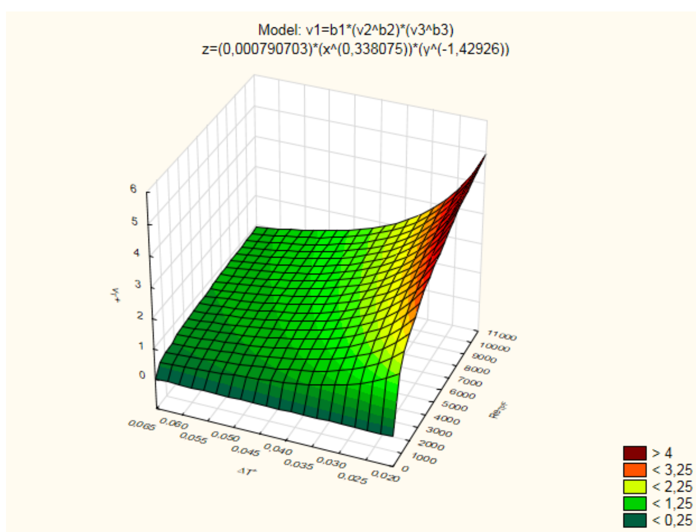

Figure 11: Interdependence of quantities forming the regression model (V^+_T, ΔT^+, $\mathrm{Re}_{\mathrm{TPF}}$, Eq. (10)) for R1234yf refrigerant during the development of the condensation process.

R1234ze, R404A, R507, and R448A. The tabular statement also indicates the range of accuracy of comparison of calculation results ($v^+_{p\ \mathrm{reg}}$) with experimental ($v^+_{p\ \mathrm{exp}}$). It was within the range of $\pm 25\%$.

Table 1: Summary of computational correlations describing quantities v_p^+ and v_T^+ for the tested refrigerants.

The model refers to	Form of the regression model equation		Refrigerant type					
	Regression model of impulsive pressure instabilities $v_p^+ = C \cdot \mathrm{Re}_{\mathrm{TPF}}^a \cdot (\Delta p^+)^b$		R134a	R1234yf	R1234ze	R404A	R507	R448A
rapid development of the condensation process	Values of unknowns	C	$18.52 \cdot 10^5$	$1.85 \cdot 10^{-6}$	$3.29 \cdot 10^6$	302.96	$4.67 \cdot 10^9$	327.8
		a	–1.06	–1.06	–1.05	–0.48	–2.27	–0.52
		b	1.05	1.05	1.72	–1.05	1.33	–1.11
	Significance coefficient r-Pearson		0.99	0.93	0.99	0.99	0.99	0.91
	Variance from population σ^2		99%	87%	99%	98%	98%	96%
	Scope of model compatibility		±20%	±20%	±20%	±25%	±25%	±25%
rapid disappearance of the condensation process	Values of unknowns	C	$46.22 \cdot 10^4$	$38.36 \cdot 10^{-4}$	$95.54 \cdot 10^4$	85.95	34.6	16.46
		a	–0.94	–0.90	–0.99	0.0095	0.12	0.18
		b	0.84	0.85	0.89	–1.034	–1.04	–0.80
	Significance coefficient r-Pearson		0.98	0.93	0.99	0.97	0.96	0.97
	Variance from population σ^2		97%	97%	99%	93%	91%	93%
	Scope of model compatibility		±20%	±20%	±20%	±20%	±20%	±20%
	Regression model of impulsive temperature instabilities $v_T^+ = C \cdot \mathrm{Re}_{\mathrm{TPF}}^a \cdot (\Delta T^+)^b$		R134a	R1234yf	R1234ze	R404A	R597	R448A
rapid development of the condensation process	Values of unknowns	C	0.00079	0.00079	$1.78 \cdot 10^{-6}$	$3.04 \cdot 10^{14}$	$7.58 \cdot 10^{11}$	$9.97 \cdot 10^{11}$
		a	0.34	0.34	–0.99	–2.49	–2.20	–2.28
		b	–1.43	–1.43	0.89	3.93	2.80	2.64
	Significance coefficient r-Pearson		0.99	0.99	0.99	0.96	0.99	0.95
	Variance from population σ^2		98%	98%	99%	92%	98%	96%
	Scope of model compatibility		±20%	±25%	±25%	±20%	±20%	±20%
rapid disappearance of the condensation process	Values of unknowns	C	29.42	0.014	0.013	$101 \cdot 10^9$	$4.67 \cdot 10^9$	$1.54 \cdot 10^9$
		a	0.65	–0.23	–0.20	–2.47	–2.67	–2.13
		b	2.97	–1.99	–1.79	1.85	1.33	1.22
	Significance coefficient r-Pearson		0.99	0.99	0.99	0.96	0.99	0.99
	Variance from population σ^2		98%	98%	98%	89%	98%	98%
	Scope of model compatibility		±20%	±20%	±20%	±20%	±20%	±20%

4 Conclusions

The paper proposes proprietary computational models for determining the propagation velocity of pressure and temperature instabilities during the development or disappearance of the liquefaction process of existing and new environmentally friendly refrigerants. The proposed calculation methods were based on a regression function in which the expected value of the explained variable depends on the explanatory variables. In the case under consideration, the explanatory variable was the value of the propagation velocity of a given instability, while the explanatory variables were related to the parameters of the system.

Simple dimensional analysis procedures were used, taking into account the Buckingham Π theorem. A general form of the regression function was obtained with the help of the values of the dimensionless velocity of propagation of pressure instabilities and the dimensionless velocity propagation of temperature instabilities for different refrigerants. Calculations made according to the developed models were compared with experimental studies. Satisfactory agreement was shown, within $\pm 25\%$, for all analyzed factors. This result should be considered satisfactory and testifies to the applicability of the developed regression models for the computational determination of the propagation speed of pressure and temperature instabilities originating from unitary dynamic interactions. The 25% accuracy interval value for two-phase flows is a very good result in two-phase flow technology, as indicated in the industry literature.

The methodology proposed by the author makes it possible to calculate significant quantities (the dimensionless velocities of propagation of pressure and temperature instabilities) in describing the dynamic unit instabilities that occur in the liquefaction process in mini-channels. Using a relatively simple method, important information was obtained that effectively fills a gap in the literature.

It should be emphasized that the proposed methodology can be applied to new agents that are replacements for phased-out F-gases.

Received 17 January 2023

References

[1] Benzi R., Sutera A., Vulpiani A.: *The mechanism of stochastic resonance.* J. Phys. A: Math. Gen. **14**(1981), 1453–l457.

[2] Bergles A.E., Kandlikar S.G.: *On the nature of critical heat flux in microchannels.* J. Heat Transfer-T ASME **127**(2005), 1, 101–107.

[3] Daisuke J., Mikajiri N., Nobunaga M., Inoue N.: *Condensation heat transfer of pure refrigerants R1234yf and R32 inside multiple circular minichannels.* Int. J. Heat Mass Tran. **195**(2022), 123146.

[4] Darcy D.F.: *On acoustic propagation and critical mass flux in two-phase flow.* J. Heat Transfer-T ASME **93**(1971), 4, 413–421.

[5] Fauve S., Heslot F.: *Stochastic resonance in a bistable system.* Phys. Lett. A **97**(1983), 1–2, 5–7.

[6] Gammaitoni L., Hänggi P., Jung P., Marchesoni F.: *Stochastic resonance.* Rev. Mod. Phys. **70**(1998), 1, 223–287.

[7] Ghiaasiaan S.M.: *Two-Phase Flow, Boiling, and Condensation in Conventional and Miniature Systems.* Cambridge Univ. Press, 2008.

[8] Gmurman W.J.: *Probability and Mathematical Statistics.* WNT, Warszawa 1975.

[9] Gubaidullin D.A., Gubaidullina D.D., Fedorov Y.V.: *About the equilibrium speed of sound in a liquid with gas-vapor bubbles.* J. Phys.: Conf. Ser. **669**(2016), 1, 012011. doi: 10.1088/1742-6596/669/1/012011

[10] Hanamura K., Kaviany M.: *Propagation of condensation front in steam injection into dry porous media.* Int. J. Heat Mass Tran. **38**(1995), 8, 1377–1386.

[11] Helmholtz H.: Verhandlungen des Naturhistorisch-medizinischen Vereins zu Heidelberg, **III(**1863), 16.

[12] Kuczyński W., Charun H., Piątkowski P., Bałasz B., Chliszcz K.: *A regressive model for dynamic impulsive instabilities during the condensation of R134a, R1234ze(E) and R1234yf refrigerants.* Int. J. Heat Mass Tran. **169**(2021), 120963.

[13] Kuczyński W., Charun H., Bohdal T.: *Impact of periodically generated hydrodynamic disturbances on the condensation efficiency of R134a refrigerant in pipe minichannels.* Exp. Heat Transfer **26**(2013), 1, 64–84.

[14] Kuczyński W., Charun H.: *Modeling of a two-phase region length of the condensation of R134a and R404A refrigerants in pipe minichannels with periodic hydrodynamic instabilities.* Heat Transfer Eng. **35**(2014), 9, 850–862.

[15] Kuo C.-J., Peles Y.: *Flow boiling instabilities in microchannels and means for mitigation by reentrant cavities.* J. Heat Transfer-T. ASME **130**(2008), 7, 072402. (Also Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, **130**(2008)).

[16] Longo G., Mancin S., Righetti G., Zilio C.: *Saturated vapour condensation of R134a inside a 4 mm ID horizontal smooth tube: Comparison with the low GWP substitutes R152a, R1234yf and R1234ze(E).* Int. J. Heat Mass Tran. **133**(2019), 461–473.

[17] López-Belchí A.: *Assessment of a minichannel condenser at high ambient temperatures based on experimental measurements working with R134a, R513A and R1234yf.* Appl. Therm. Eng. **155**(2019), 341–353.

[18] Mainil A.K., Sakamoto N., Ubudiyah H., Miyara A., Kariya K.: *Experimental study and general correlation for frictional pressure drop of two-phase flow inside microfin tubes.* Int. J. Refrig. **144**(2022), 342–353.

[19] Moody F.J.: *A pressure of pulse model for two-phase critical flow and sonic velocity*. J. Heat Transfer-T. ASME **91**(1969), 3, 371–384.

[20] Pham Q.V., Oh J.-T.: *Condensation heat transfer characteristics of R1234yf inside multiport minichannel tube*. Int. J. Heat Mass Tran. **170**(2021), 121029.

[21] Shin J.S., Kim M.H.: *An experimental study of condensation heat transfer inside a minichannel with a new measurement technique*. Int. J. Multiphas. Flow **30**(2004), 311–325.

[22] Teng R., Cheng P., Zhao T.S.: *Instability of condensate film and capillary blocking in small-diameter-thermosyphon condensers*. Int. J. Heat Mass Tran. **42**(1999), 16, 3071–3083.

[23] Wang L., Jiao P., Dang Ch., Hihara E., Dai B.: *Condensation heat and mass transfer characteristics of low GWP zeotropic refrigerant mixture R1234yf/R32 inside a horizontal smooth tube: An experimental study and non-equilibrium film model development*. Int. J. Therm. Sci. **170**(2021), 107090.

[24] Weisman J., Ake T., Knott R.: *Two-phase pressure drop across abrupt area changes in oscillatory flow*. Nucl. Sci. Eng. **61**(1976), 3, 297–309.

[25] Welander P.: *On the oscillatory instability of a differentially heated loop*. J. Fluid. Mech. **29**(1967), 1, 17–30.

[26] Yuncu H., Yildirim O.T., Kakac S.: *Two-phase flow instabilities in a horizontal single boiling channel*. J. Appl. Sci. Res. **48**(1991), 83–104.