Article

Experimental Study of Nucleate Boiling of Flammable, Environmentally Friendly Refrigerants

Bartosz Gil * and **Beata Fijałkowska**

Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland; 221858@student.pwr.edu.pl
* Correspondence: bartosz.gil@pwr.edu.pl

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Abstract: This paper investigates the nucleate boiling process of dimethyl ether and selected hydrocarbons. The main goal of this study is to measure the heat transfer coefficients of RE170, R600a, and R601, and to compare them with R134a. The experiments were carried out for heat fluxes up to 70 kW/m^2. Experimental results have shown a typical trend that the heat transfer coefficient of flammable refrigerants increases as the heat flux increases. Among the tested fluids, the highest values of heat transfer coefficient were obtained for RE170. Available correlations describing this coefficient showed a deviation of up to 93%, as compared to the data obtained. The new correlation was developed by regression analysis taking into account dimensionless variables affecting the boiling process.

Keywords: pool boiling; hydrocarbons; dimethyl ether; alternative refrigerants; low global warming potential (GWP); RE170

1. Introduction

Nowadays, great emphasis is placed on protecting the atmosphere and limiting climate change. For these reasons, working fluids currently used are being phased out and replaced by a fourth generation of refrigerants, mainly by low global warming potential (GWP) hydrofluorocarbons (HFCs) and natural substances with a negligible GWP. A common option for replacing halogenated refrigerants is the use of hydrocarbons (HCs). These are naturally occurring and inexpensive substances that can be used in a wide range of refrigeration equipment. In addition, they have zero ozone depletion potential (ODP) and very low GWP. Moreover, hydrocarbons are not only good for the environment, but can also be more efficient heat conductors than halogenated refrigerants [1]. Their use is not limited to pure refrigerants. They are common components of mixtures that can significantly reduce the environmental impact. However, considering the use of flammable refrigerants, such as hydrocarbons, it is necessary to pay attention to safety concerns. All hydrocarbons belong to the A3 safety group, which means high flammability. Therefore, safety regulations require the installation of appropriate devices preventing excessive pressure build-up and the use of special electrical installation solutions. Reliable ventilation is also required in spaces where a combustible hydrocarbon–air mixture can be formed, due to leakage from the installation.

Following legal requirements, it is necessary to constantly search for substances that can replace refrigerants that are harmful to the environment and to examine their properties. A great deal of research has been done to investigate the performance of compressor systems using hydrocarbons instead of traditional refrigerants. Energy and exergy analysis of a domestic refrigerator filled with R290, R600, and commercial LPG as an alternative to R134a was carried out by El-Morsi [2]. The results showed that the highest coefficient of performance (COP) and exergetic efficiency was obtained by R600a. Mohanraj [3] studied the possibility of using R430A as R134a replacement in a domestic

refrigerator. The conclusion was that the refrigeration capacities of the system with R430A and R134a were comparable, but the COP of the system with R430A was higher than that of R134a by up to 7.5%, and the power consumption was lower. Similar conclusions regarding other hydrocarbons and their mixtures are presented in [4,5].

In addition to hydrocarbons, dimethyl ether (DME, RE170) is a natural substance that, in recent years, has been considered an alternative to F-gases (HFCs). It is produced from natural gas, coal, or biomass using a methanol dehydration reaction (Figure 1). DME is a colorless gas with low viscosity and a characteristic odor. This substance dissolves moderately in water [6]. It is a gas that liquefies easily (the liquefaction temperature is −25 °C), so it can be transported over long distances [7].

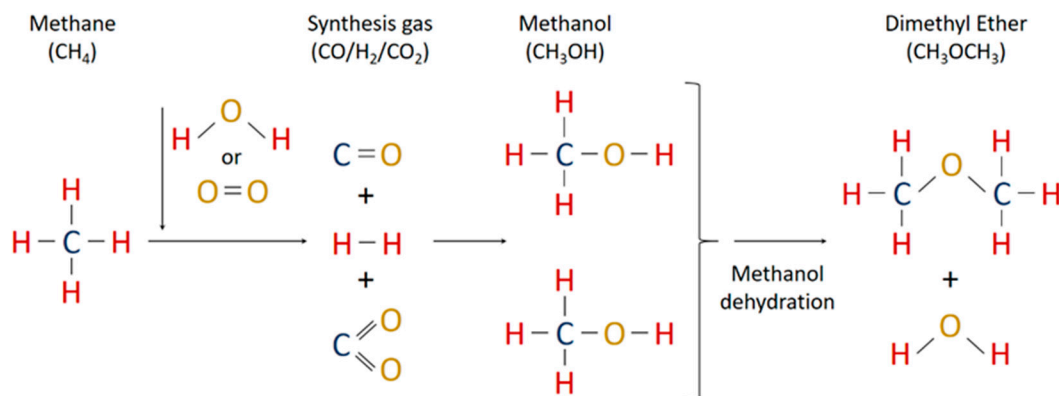**Figure 1.** The dehydration of methanol to dimethyl ether.

Dimethyl ether is fully environmentally friendly (ODP = 0, GWP = 1) and meets the requirements for refrigerants after 2020 under EU Regulation 517/2014 [8]. It has a low boiling point and high latent heat of vaporization. In addition, it is non-toxic and does not cause corrosion. Compared to refrigerants from the HFC group (e.g., R134a), it is much cheaper while maintaining a comparable cooling effect [9]. Dimethyl ether as a homogeneous fluid does not show temperature glide, so it has an advantage over zeotropic mixtures. It does not separate during the leakage, does not tend to self-oxidation, and is stable when interacting with oxygen from the air. Unfortunately, dimethyl ether also has disadvantages, mainly associated with contact with the human body. DME vapors cause severe eye irritation, and in high concentrations heart failure, loss of consciousness, and possibly death. Dimethyl ether also has a narcotic effect. Frostbite may occur through contact of liquid DME with the skin [6], which is typical for most refrigerants.

Research conducted by Apostol et al. [10] showed that RE170 can be used as a replacement for R22 and R134a in compression refrigeration systems. Compared to R134a, RE170 has higher COP and better heat exchange. It is also compatible with mineral oils and residual R134a. DME does not react with ferrous materials, copper and its alloys, or aluminum. DME is also used as a mixture with R152a in an 80/20 weight share. This mixture, defined as R435A, reaches a COP that is 5.7% higher than that of pure R134a [11]. Another DME-containing mixture is R510A, an azeotropic mixture consisting of RE170 and R600a (88 and 12% by weight, respectively), which successfully replaces R134a in compressor refrigeration [12]. In addition to single-stage cooling cycles, DME is also used in cascade systems. The mixture of R744 and RE170 (the weight share of dimethyl ether in the high pressure circuit and in the low pressure circuit are 20 and 10%, respectively) shows very good effects when working in cascade systems. It allows for better system efficiency, lower compressor power, a lower mass flow rate, and lower exergy losses compared to the use of pure fluids [13]. DME is considered to be an alternative to R134a, so the flammability of the mixture consisting of R134a and RE170 has been investigated [9]. The lower and upper flammability limits were determined, and it was shown that, at a ratio of non-flammable R134a to flammable DME equal to 5, the mixture ignites (lower and upper flammability limits meet). Zhai et al. [14] checked the miscibility of RE170 with mineral oils. The final

effect was the determination of the Z_{so} parameter, which determines the ability to form a mixture with mineral oil. Of the 16 substances tested, DME was the fourth, just after isobutane, compound that dissolves mineral oils well ($Z_{so} = 0.03 > 0$). As a replacement for R134a, RE170, similarly to hydrocarbons, both pure and in mixtures, can be used in domestic refrigerators, transport refrigeration, as well as stationary and mobile air conditioning systems.

The knowledge and amount of data on dimethyl ether is limited due to its relatively short use in refrigeration. The comprehensive design of a cooling device requires knowledge of many thermodynamic aspects of refrigerant operation. Therefore, research on the thermodynamic properties and basic transformations implemented in the refrigeration cycle is still being carried out. Determination of thermodynamic properties is possible thanks to the equation of state, for which experimental data such as vapor pressure, gas heat capacities, and critical point parameters are necessary. The literature shows a small range of this data, which is why research is conducted to expand the scope of available knowledge. Ihmels and Lemmon [15] carried out density measurements at temperatures from 273 to 523 K at pressures between 0.87 and 40 MPa and vapor pressures between 264 and 194 kPa. The critical point was determined visually. These data were used to develop the basic state equation for dimethyl ether. Basic properties of pure refrigerants and blends mentioned in this work are included in Table 1.

Table 1. Basic properties of selected refrigerants.

		R134a	R430A	R435A	R510A	RE170	R600a	R601
Name		1,1,1,2-tetrafluoroethane	–	–	dimethyl ether	isobutane	pentane
Classification		HFC	HFC	HFC	HC	n/a	HC	HC
Safety classification		A1	A3	A3	A3	A3	A3	A3
ATEL/ODL	kg/m^3	n/a	0.105	0.098	0.089	0.079	0.06	0.003
LFL	kg/m^3	0.21	0.084	0.068	0.056	0.064	0.038	0.035
Molar mass	kg/kmol	102.03	63.96	49.04	47.24	46.07	58.12	72.15
Normal boiling point	°C	−26.1	−27.4	−25.8	−24.9	−24.8	−11.7	36.1
Critical temperature	°C	101.1	107.0	123.1	125.7	127.2	134.7	196.6
Critical pressure	kPa	4059.3	4089.1	5191.9	5118.6	5336.8	3629.0	3367.5
Critical density	kg/m^3	511.9	316.5	289.1	268.6	273.6	225.5	231.6
Evaporating pressure [1]	kPa	414.61	411.14	388.82	372.09	373.35	220.61	37.84
Latent heat of vaporization [1]	kJ/kg	190.74	289.32	392.45	407.93	421.75	344.63	377.66
Thermal conductivity [1]	W/(mK)	0.0876	0.0963	0.1272	0.1282	0.1326	0.0948	0.1176
Surface tension [1]	N/m	0.0100	0.0105	0.0129	0.0134	0.0134	0.0117	0.0171
ODP		0	0	0	0	0	0	0
GWP		1430	93	24	1	1	3	5

[1] for saturation temperature 10 °C; n/a—not applicable.

Most of these tests are carried out to find out the physical and chemical properties of DME, so as to confirm the possibility of using it as a replacement for R134a. The aim of this study was to investigate the heat transfer process of dimethyl ether and selected hydrocarbons, and to compare them with R134a. The substances selected for experimental research are now the core around which new ecological refrigerants are built. Therefore, expanding knowledge of the boiling process of these components is crucial for the refrigeration equipment design process.

2. Experimental Setup, Procedure, and Measurement Errors

In this paper, the nucleate boiling heat transfer coefficients of dimethyl ether (RE170), isobutane (R600a), and pentane (R601) were experimentally determined and are presented. The measurements were carried out on a flat plate with a diameter of 72 mm. Figure 2 shows the experimental set-up, which consists of two brass flanges and a stainless steel tube having a diameter of 80 mm and a length of 300 mm. Each time, 400 g of test substances were fed into the tank through the filling port. The boiling process took place in the lower part of the vessel due to heat supply through the heating element. The current heating power was determined using an autotransformer and measured with a wattmeter. In the upper part, the steam generated condensed on the working surface of the condenser, which was fed with chilled water. The condenser has a spiral shape with an external coil diameter of 60 mm. The

whole bench was insulated with polyurethane foam. A total of 6 temperature sensors for measuring the temperature of the heating surface (resistance thermometer PT100, 1/3 DIN), the temperature of the stainless steel tube (three thermocouples type K, class 1), and the temperature of the cooling water at the inlet and outlet from the condenser (two thermocouples type K, class 1) were installed in the stand. The sensor measuring the temperature of the heating surface was located 1 mm below this surface in the drilled hole. Thermal contact between the sensor surface and the working surface was achieved by filling the hole with thermal grease paste with a thermal conductivity of 73 W/(mK). Due to the tight fit of the sensor in the hole and earlier filling it with thermally conductive paste, when calculating the heat transfer coefficient, the temperature change resulting from the inaccuracy of the sensor contact with the surface was not taken into account. Only the sensor mounting location and thermal conductivity of the heating surface material were considered. Thermocouples mounted on the shell were used to control the wall temperature and made it possible to correct the obtained results by the value of heat losses. However, due to the good insulation of the device, the differences between the fluid saturation temperature and the wall temperature were small enough to be neglected. The pressure value was measured with an absolute pressure gauge together with a transducer Keller-Druck PAA33X-EV-120. All measured signals were connected to the LUMEL KD7 data acquisition system.
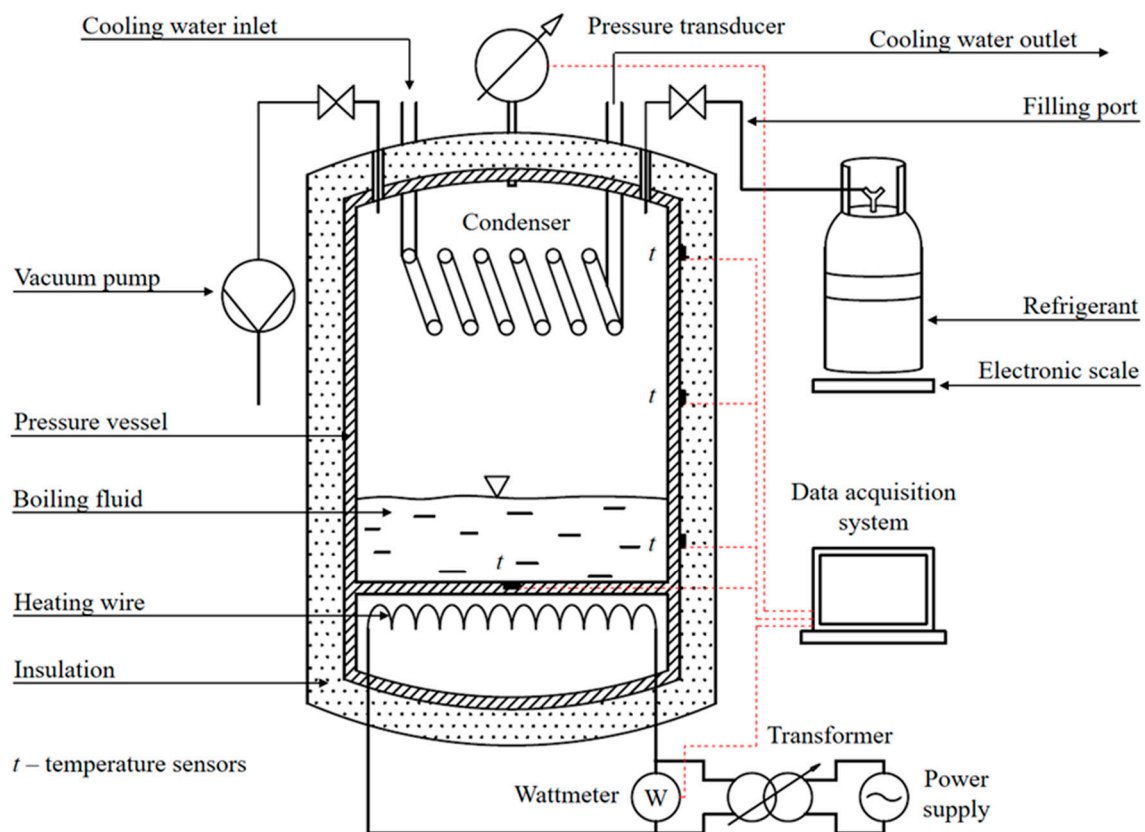

Figure 2. Experimental set-up.

During the tests, the heat flux was gradually increased to its maximum of about 70 kW/m^2. After reaching the maximum, the heat flux was gradually reduced to zero. It was assumed that the pressure measured by the manometer is equal to that prevailing in the boiling liquid, and on that basis, using the property tables [16], the saturation temperature for tested refrigerants was obtained. The experiment was conducted in such a way that complete evaporation of the liquid was avoided, which would result a sharp decrease in heat transfer coefficient.

In a pool boiling experiment, the wall superheat was measured versus the heat flux, which allowed for the nucleate boiling heat transfer coefficient using Equation (1):

$$h_{nb} = \frac{q}{\Delta T} = \frac{q}{(t_1 - t_2)} \tag{1}$$

where

t_1—temperature of the heating surface, °C;
t_2—boiling point temperature of the refrigerant (determined on the basis of the saturation pressure reading), °C.

In addition, during surface temperature measurements, efforts were made to take into account the thermal resistance of the brass wall between the position of the sensor and the actual boiling surface. All probes were calibrated according to the calibration in the liquid bath method (comparative method), with water as the control liquid. The uncertainties of the errors of the measured parameters are presented in Table 2. Using the law of propagation of uncertainties as a geometric sum of partial differentials, the standard uncertainty of the heat transfer coefficients was also determined.

Table 2. Measuring errors of the instruments used.

Measurand	Sensor Type	Uncertainty
Temperature	PT 100 1/3 DIN	0.09 K
	Thermocouple K-type, class 1	0.2 K
Pressure	PAA-33X	0.1 kPa (for R601) 1 kPa (for RE170, R600a)
Heating power	Wattmeter LW-1, class 0.5	2 W
Heating area	–	0.02%

3. Experimental Results

Three flammable refrigerants of dimethyl ether (RE170), isobutane (R600a), and pentane (R601) were selected for pool boiling experimental tests. All experiments were performed at a liquid saturation temperature of 10 °C, on a horizontal flat plate, with heat fluxes from 5 to 70 kW/m^2, for both increasing and decreasing heat fluxes.

Experimental values of the heat transfer coefficients are shown in Figure 3. All tested liquids show a typical trend: as the heat flux increases, the heat transfer coefficient also increases. This confirms the theory of boiling that, with increasing heat flux, an increasing number of nucleation sites are activated until the entire surface is covered with bubbles, which grow and depart rapidly. In addition, the hysteresis field is clearly marked for dimethyl ether and isobutane. This arises from the activation of subsequent nucleation sites with a change in heat flux. The first series of measurements (increasing the heat flux) is characterized by lower values of the heat transfer coefficient, due to the limited number of nucleation sites, in which bubble formation and growth occur. The second measurement series (lowering the heat flux) gives higher values of the heat transfer coefficient, as the places previously activated by the higher heat flux remain active. It is important to note that the change in the heat transfer coefficient is significant, especially in the heat flux range below 30 kW/m^2, where the increase is as high as 25% for RE170 and 30% for R600a. A somewhat different behavior was observed for pentane, where the change in the value of the heat transfer coefficient is almost invisible.
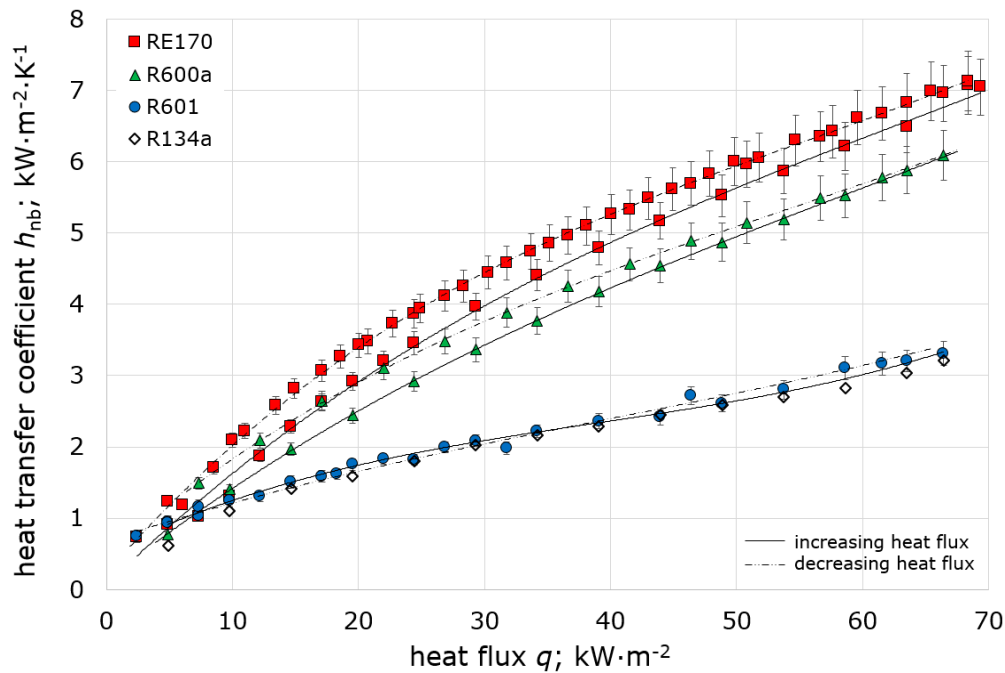
Figure 3. Nucleate boiling heat transfer coefficient for different heat fluxes.

RE170 yields the highest heat transfer coefficients, obtaining a maximum value of 7.1 kW/(m^{2}K). Specifically, it is 15% higher than that of R600a and more than twice as high as that of R601. The saturation pressure is undoubtedly the parameter causing low heat transfer coefficients for pentane. It was the only fluid tested deep under pressure (around 38 kPa), where for comparison the saturation pressures of dimethyl ether and isobutane were 370 and 220 kPa, respectively. Meanwhile, in the correlations of the boiling process, the importance of the factor associated with the saturation pressure or the saturation temperature of the working fluid is clear.

Experimental results for R134a were also presented for comparative purposes. The substances described and analyzed in this paper can be direct substitutes for this refrigerant, which is used on a large scale in refrigeration equipment with medium and high evaporation temperatures. R134a obtains values close to R601, which is important in the context of its replacement with the presented fluids. This means that none of the fluids presented in this work are worse than R134a. In addition, considering that the tested flammable refrigerants are characterized by a significantly higher heat of evaporation and that they obtain higher heat transfer coefficient values (in the case of RE170 and R600a), it can be concluded that the use of this fluids in a real heat exchangers will allow both to reduce their surfaces and the filling (amount) of the refrigerant.

Experimentally obtained boiling curves for tested flammable refrigerants are shown in Figure 4. The boiling curves for RE170 and R600a have an almost identical slope. The curves for isobutane shift slightly towards greater superheating (the difference from RE170 does not exceed 2 K). A clearly different shape of the boiling curve was observed for pentane (R601). A clear shift towards higher superheating as well as a smaller gradient of the boiling curve are visible. The transition point from the natural convection regime to the nucleate boiling regime, described as the onset of boiling (ONB), is clearly visible for dimethyl ether and occurs for a heat flux of around 10 kW/m^2. In the diagram, this is the point where the slope of the curve increases significantly.
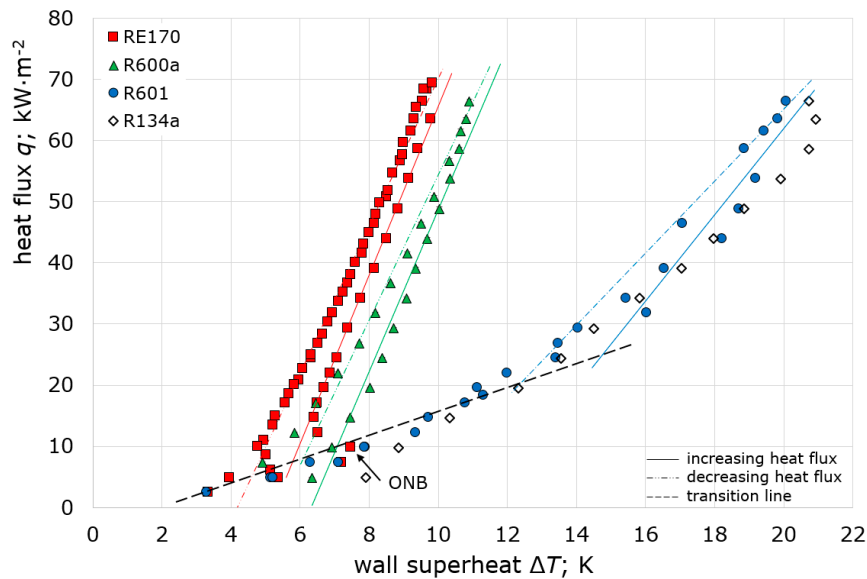
Figure 4. Boiling curves.

4. Pool Boiling Correlation Comparison and Development

Since new alternative refrigerants appear on the market, it is necessary to accurately determine their operating parameters. One of the most important issues from the point of view of refrigeration cycle operation is the phase change process that occurs in the evaporator. Knowledge of the heat transfer parameter can allow one to determine the minimum evaporator surface necessary to ensure the required cooling capacity. This is of key importance in the design process of evaporators of refrigeration equipment, which allows one not only to design a refrigeration system that meets the assumed parameters, but also to avoid unnecessary costs associated with the oversizing of the heat exchanger. Therefore, it is extremely important to determine the correct correlations describing the boiling process and the value of the heat transfer coefficients.

The boiling process is affected by a number of parameters, of which the most important are the properties of the substance, such as thermal conductivity, density, and surface tension, as well as the parameters of the working surface and the process itself, such as heat flux density, boiling temperature, and surface superheating, as shown in Equation (2).

$$h_{nb} = f(\Delta T, k, \sigma, \rho, d_0, q, \ldots) \tag{2}$$

Hence, the mathematical description of the boiling process is a very complex issue. Most often it comes down to determining the correlations that allow for calculations of the heat flux or the heat transfer coefficient in relation to the boiling liquid in specific conditions. The complexity of the boiling process means that accurate, reliable design equations will continue to appear.

There are many correlations available in the literature, but only some are often used to determine heat transfer coefficients [17]. These include correlations presented by various authors:

1. Stephan and Abdelsalam [18] used the physical properties of the substance in Equation (3).

$$\frac{h_{nb}d_0}{k_L} = 0.0546 \left[\left(\frac{\rho_G}{\rho_L} \right)^{0.5} \frac{q d_o}{k_L T_{sat}} \right]^{0.67} \left(\frac{h_{LG}d_0^2}{a_L^2} \right)^{0.248} \left(\frac{\rho_L - \rho_G}{\rho_L} \right)^{-4.33}. \tag{3}$$

In the above equation, the bubble departure diameter d_0 was determined by Equation (4).

$$d_0 = 0.0146\beta \left[\frac{2\sigma}{g(\rho_L - \rho_G)} \right]^{0.5}. \tag{4}$$

2. Cooper [19] presented the heat transfer coefficient as a function of the heat flux, the reduced pressure, the molecular weight of the liquid, and the working surface roughness. The reduced pressure correlation of Cooper takes the form of Equation (5).

$$h_{nb} = 55 p_r^{0.12-0.4343lnR_p} \left(-log_{10}p_r\right)^{-0.55} M^{-0.5} q^{0.67}. \tag{5}$$

For undefined surfaces, the roughness in the above formula is 1.0 μm. The correlation applies to reduced pressure in the range from 0.001 to 0.9 and a molecular weight of boiling fluid from 2 to 200 kg/kmol.

3. Kutateladze [20] simplified Kruzhilin's [21] correlation, which did not take the surface properties into account. In this correlation, Equation (6), the bubble diameter was estimated using the Fritz type equation, expressed in Equation (7).

$$h_{nb} = 0.44 P_r^{0.35} \frac{k_L}{d_0} \left(\frac{\rho_L}{\rho_L - \rho_G} \frac{p \cdot 10^{-4}}{\rho_G g h_{LG} \mu_L} q \right)^{0.7} \tag{6}$$

$$d_0 = \left[\frac{\sigma}{g(\rho_L - \rho_G)} \right]^{0.5} \tag{7}$$

4. More recently, Ribatski and Jabardo [22] experimentally investigated the nucleate boiling heat transfer coefficient of halocarbon refrigerants. Their research included five refrigerants (R11, R123, R12, R134a, and R22), in a range of reduced pressure from 0.008 to 0.26, for two surface roughness values and three surface materials; Equation (8) applies to boiling on a brass surface.

$$h_{nb} = 110 R_a^{0.2} p_r^{0.45} \left(-log_{10}p_r\right)^{-0.8} M^{-0.5} q^{0.9-0.3p_r^{0.2}}. \tag{8}$$

5. Jung et al. [23] conducted a study to compare heat transfer coefficients for five flammable refrigerants, including DME. Based on the proposed correlation, Equation (9), it is possible to determine the heat transfer coefficient for both halogen and flammable refrigerants.

$$h_{nb} = 41.4 \frac{k_L}{d_0} \left[\frac{q d_o}{k_L T_{sat}} \right]^{C_2} \left(-log_{10}p_r\right)^{-1.52} \left(1 - \frac{\rho_G}{\rho_L} \right)^{0.53}. \tag{9}$$

In the above equation, the same formula as that used by Stephan and Abdelsalam [18] was used to determine the bubble departure diameter.

In order to quantify the obtained experimental results, the five correlations above were taken into account for comparative purposes. All thermodynamic and transport properties necessary for calculations were taken from REFPROP v. 9.1 [16]. The comparison was made by determining the average deviation of a given correlation from experimental data, in Equation (10).

$$\textit{Average deviation} = \frac{1}{n} \sum_{i=1}^{n} \frac{\left| (correlation\ value) - (experimental\ value) \right|}{(experimental\ value)}. \tag{10}$$

The average correlation deviations in relation to the experimental heat transfer coefficient are presented in Table 3, while the deviations for individual measuring points are shown in Figure 5. When calculating the average deviation, only the nucleate boiling regime was taken into account; namely, the measuring points in the natural convection regime were omitted.

Table 3. The average correlation deviations.

	Stephan and Abdelsalam	Cooper	Kutateladze	Ribatski and Jabardo	Jung et al.
RE170	2.0%	37.7%	33.5%	93.6%	5.9%
R600a	3.0%	34.9%	44.6%	88.4%	7.5%
R601	8.2%	25.8%	33.2%	49.1%	23.0%

From the equations presented, Stephan and Abdelsalam's correlation yields the lowest average deviation of 2.0, 3.0, and 8.2% for RE170, R600a, and R601, respectively. A good fit for RE170 and R600a is also obtained by Jung et al.'s correlation: 5.9 and 7.5%, respectively. The development of this correlation was not based on experimental data for pentane, which is reflected in high inaccuracy. The correlations of Cooper as well as Ribatski and Jabardo greatly overestimate the heat transfer coefficient, which is why using these formulas for the tested hydrocarbons is not recommended. On the other hand, 30–40% underestimation of the heat transfer coefficient was obtained using the Kutateladze correlation.
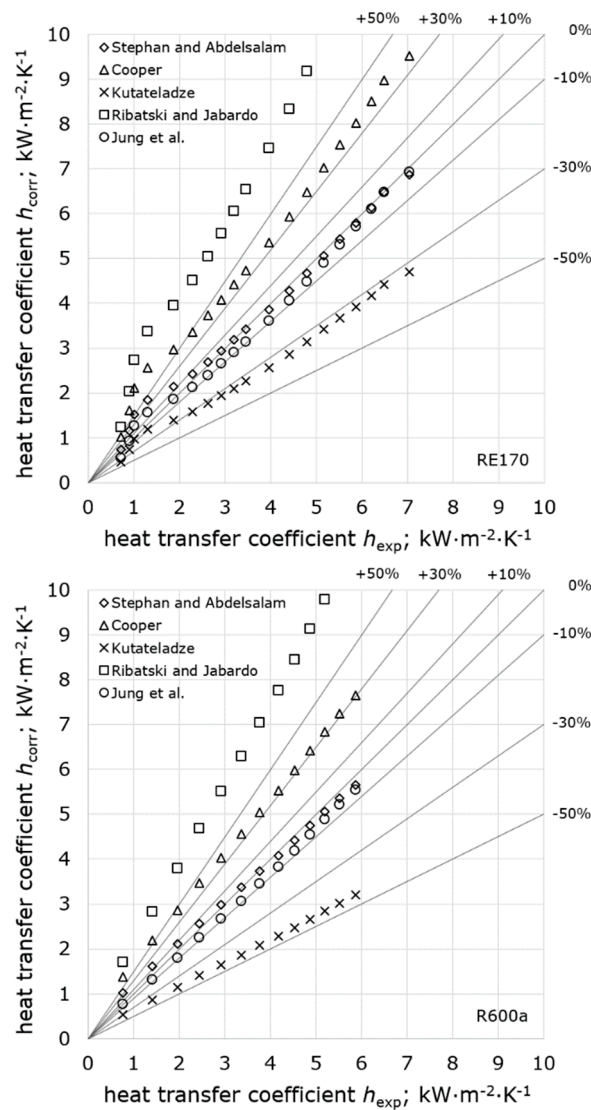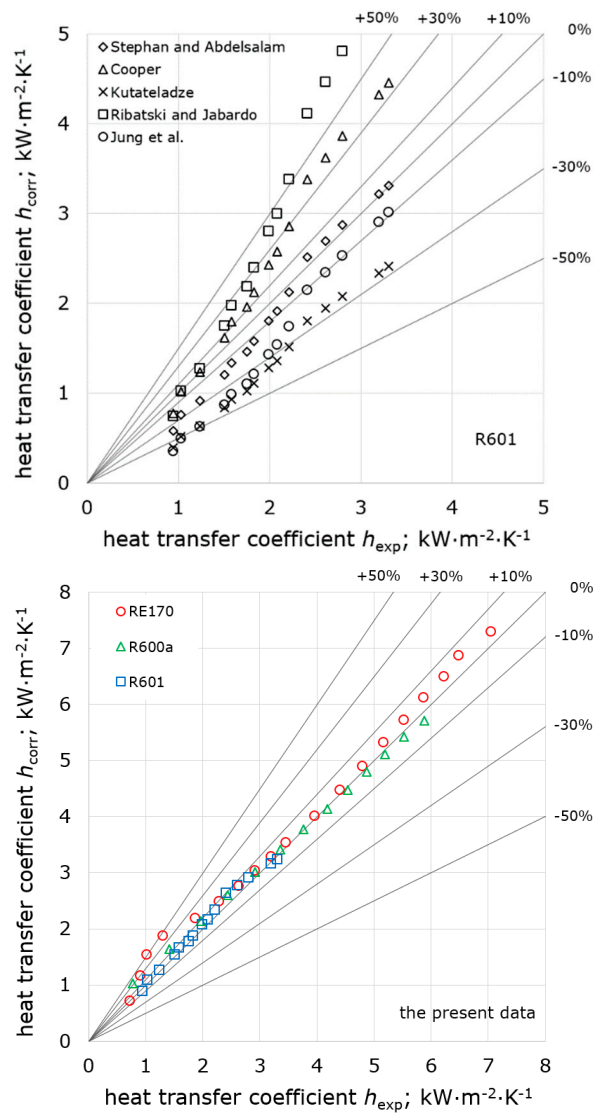

Figure 5. *Cont.*

Figure 5. Comparison between various correlations and the present data.

Based upon the measured data of the three hydrocarbons tested and following the approaches presented in [24], a new correlation was developed. The following formula, Equation (11), was found to be the optimal correlation describing the boiling process of the three analyzed flammable refrigerants:

$$h_{nb} = 42 \frac{k_L}{d_0} \left[\frac{qd_o}{k_L T_{sat}} \right]^{C_1} (-log_{10} p_r)^{-1} \tag{11}$$

$$C_1 = 0.4 p_r^{0.78} \left(\frac{\rho_G}{\rho_L} \right)^{-0.59}. \tag{12}$$

Determination of the bubble departure diameter was based on the original Fritz equation, Equation (13), in which the contact angle β for all tested substances is constant and amounts to 35°.

$$d_0 = 0.0208 \beta \left[\frac{\sigma}{g(\rho_L - \rho_G)} \right]^{0.5}. \tag{13}$$

The deviation of the developed correlation is shown in Figure 5. The average deviation for all analyzed fluids is below 3.5%.

5. Conclusions

In this investigation, nucleate boiling heat transfer coefficients for three refrigerants, RE170, R600a, and R601, have been determined. Maximum heat transfer coefficients equal to 7.1 kW/(m^{2}K), 6.1 W/(m^{2}K), and 3.3 W/(m^{2}K), were found for RE170, R600a, and R601, respectively. Five pool boiling correlations were compared with the results, and among these, Stephen and Abdelsalam's showed the best fit. Jung et al.'s correlation reasonably predicts the heat transfer coefficients of dimethyl ether and isobutane, but under-predicts the value for pentane by over 20%. The remaining three correlations did not reliably determine the heat transfer coefficients of the tested refrigerants. Based on these experimental results, these fluids, especially RE170, are viable options as replacements for high-GWP refrigerants currently used. Based on the obtained experimental results and on regression analysis, a formula was developed to determine the heat transfer coefficients of the tested flammable refrigerants. The correlation obtained predicts the value of heat transfer coefficients with an average deviation of up to 3.5%. Its advantage over other correlations is also a more accurate determination of the heat transfer coefficient of R601. As the presented flammable refrigerants very often constitute one of the components of refrigeration blends, additional testing may prove useful in understanding the effect of the composition of the blends containing these fluids on the boiling process.

Author Contributions: Data curation: B.F.; formal analysis: B.G.; investigation: B.G.; methodology: B.G.; visualization: B.G.; writing—original draft: B.G. and B.F. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

a	thermal diffusivity, m^2·s^{-1}
d_0	bubble departure diameter, m
g	gravitational acceleration, m·s^{-2}
h_{LG}	heat of evaporation, kJ·kg
h_{nb}	nucleate boiling heat transfer coefficient, W·m^{-2}·K^{-1}
k	thermal conductivity, W·m^{-1}·K^{-1}
M	molecular weight, kg·kmol^{-1}
p	pressure, Pa or kPa
p_r	reduced pressure, −
q	heat flux, W·m^{-2}
R_a, R_p	surface roughness, μm
T, ΔT	temperature, temperature difference, K
Greek letters	
β	contact angle, °
μ	viscosity, Pa·s
ρ	density, kg·m^{-3}
σ	surface tension, N·m$^{-/1}$
Subscripts	
L	liquid
G	gas, vapor
sat	saturation
corr	correlation
exp	experimental
Abbreviations	
ATEL	acute-toxicity exposure limit
ODL	oxygen deprivation limit
LFL	lower flammability limit

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