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Carbon dioxide heat transfer coefficients and pressure drops during flow boiling: Assessment of predictive methods

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ABSTRACT

Among the alternatives to the *HCFCs* and *HFCs*, carbon dioxide emerged as one of the most promising environmentally friendly refrigerants. In past years many works were carried out about CO_2 flow boiling and very different two-phase flow characteristics from conventional fluids were found.

In order to assess the best predictive methods for the evaluation of CO_2 heat transfer coefficients and pressure gradients in macro-channels, in the current article a literature survey of works and a collection of the results of statistical comparisons available in literature are furnished.

In addition the experimental data from University of Naples are used to run a deeper analysis. Both a statistical and a direct comparison against some of the most quoted predictive methods are carried out. Methods implemented both for low–medium pressure refrigerants and specifically developed for R744 are used in the comparison.

Some general indications about the choice of the predictive methods dependently on the operating conditions are given.

Coefficients de transfert de chaleur et chute de pression du dioxyde de carbone lors de l'ébullition en écoulement : évaluation des méthodes prévisionnelles

Mots clés : Échangeur de chaleur ; Ébullition ; Dioxyde de carbone-synthèse ; Coefficient de transfert de chaleur ; Chute de pression ; Comparaison-expérimentation

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Nomenclature

Latin letters

A	annular flow regime
D	dryout regime
d	diameter (m)
dp/dz	pressure gradient ($kPam^{-1}$)
g	heat transfer coefficient ($Wm^{-2}K^{-1}$) or pressure gradient ($kPam^{-1}$)
G	refrigerant mass flux ($kgm^{-2}s^{-1}$)
GWP	Global Warming Potential
h_m	heat transfer coefficient at measurement section
M	($Wm^{-2}K^{-1}$)
$HCFC$	HydroChloroFluoroCarbons
HFC	HydroFluoroCarbons
HFO	HydroFluoroOlefins
I	intermittent flow regime
l	length (m)
M	mist flow region
N	number of points
ODP	Ozone Depleting Potential
p	pressure (bar)
q	heat flux (Wm^{-2})
r	radius (m)
SW	Stratified-Wavy flow regime
sd	standard deviation (%)
t	temperature (°C)
x	vapor quality
z	abscissa along the tube (m)

Greeks

Δ	difference
ε_n	error (%)
$\bar{\varepsilon}$	mean error (%)
$\lvert\bar{\varepsilon}\rvert$	mean absolute error (%)
λ	percentage of points inside an error window of ±30%

Subscripts

exp	experimental
i	inner
fr	frictional
min	minimum
max	maximum
o	outer
pred	predicted
sat	saturation

1. Introduction

In the last years the refrigeration, air conditioning and heat pump industry has been forced through major changes. In fact, due to the ozone depletion and global warming, the use of *HCFCs* was banned in the manufacture of new equipment for all applications (EC Regulation, 2037/2000, 2000) and a gradual phase-out of fluids with *GWP* higher than 150 (such as R134a) was established in mobile air conditioning systems starting from 2008 (Directive, 2006/40/EC, 2006).

Among the substitutive refrigerants (hydrocarbons, ammonia, new synthetic substances (such as *HFO*-1234yf)), carbon dioxide (or R744) distinguishes itself because it is a non toxic and non flammable fluid, it is compatible with all commons materials used in refrigeration, air conditioning and heat pump systems, it has an *ODP* equal to 0, a negligible *GWP*, a low cost and excellent thermophysical and transport properties (Cavallini and Zilio, 2006). Unfortunately its high working pressure needs the re-design of the whole system and actually leads to more expensive plants. Besides single stage vapor compression plants, that use carbon dioxide as working fluid, usually operate with a trans-critical cycle and their energetic consumptions are higher than those of plants working with traditional refrigerants.

Thanks to many research works the feasibility and the workability of the components for high pressure and trans-critical technology were demonstrated (Kim et al., 2004) and a further step should be to enable this technology to compete in the market. At this scope good results have been already obtained in several applications (Nekså et al., 1998; Yin et al., 1999; Hafner and Nekså, 2004; Papasavva et al., 2004; Sawalha, 2005), but, taking into account that the climate change is influenced also by energy consumptions during the lifetime of the refrigerating plants, it is very important to look for still improving the energy efficiency of R744 systems.

Among the components which influence the cycle efficiency, the evaporator has fundamental importance and, therefore, its design has to be very accurate. Hence, the knowledge of refrigerant heat transfer coefficients and pressure drops during flow boiling and the availability of accurate predictive methods are necessary to reduce costs, optimize system performances and save energy.

In literature several experimental studies on carbon dioxide during flow boiling in macro-channels are available (Thome and Ribatski, 2006; Ducoulombier et al., 2008): from the published articles, it can be observed that two-phase flow characteristics of R744 (such as flow-patterns, heat transfer coefficients and pressure gradients) are very different in comparison to other conventional refrigerants.

This behaviour can be explained taking into account for the different thermodynamic and transport properties of carbon dioxide. For these reasons, the predictive methods developed using experimental databases obtained mainly for refrigerants with low reduced pressures at common temperatures generally underpredict heat transfer and overpredict pressure drops for R744. The results are not satisfactory for a very accurate design of evaporators.

In this study a summary of the results available in literature on the comparison among the most quoted predictive methods and experimental data obtained during R744 flow boiling in macro-channels is presented. Besides the experimental heat transfer coefficients and pressure gradients measured at University of Naples are used to run a deeper analysis with a statistical comparison both of the whole database and of the data segregated by flow regimes (annular and intermittent) to empirical and phenomenological methods developed for traditional refrigerants and CO_2. The results of this analysis could be useful to found the best method depending on the actual working conditions.

2. Literature survey

In past years many experimental researches were carried out to investigate two-phase flow characteristics of pure CO_2 in macro-channels. At the same time, in response to a growing need for more accurate predictive methods, a large number of correlations were developed and implemented. Table 1 describes the most relevant studies on carbon dioxide flow boiling in macro-channels (the test tubes were divided in macro- and micro-channel according to a threshold diameter of 3 mm suggested by Kandlikar and Grande (2003)). In this table, the measured parameters (refrigerant heat transfer coefficients and/or pressure gradients), the tube orientation and material, the test section geometry (inner diameter, outer diameter and length), the heating method (Joule effect or secondary fluid) and the range of refrigerant mass flux, evaporating temperature, heat flux and vapor quality investigated are specified for each experimental work. It can be noticed that experiments were carried out for horizontal channels with tube diameters from 3.00 to 10.06 mm refrigerant mass fluxes from 75 to 1440 kg/m^2s, saturation temperatures from −30 to 20 °C, heat fluxes from 2 to 60 kW/m^2. About vapor quality it was not possible to precisely define the investigated ranges; however from the analysis of the databases it resulted that at high vapour qualities there are few experimental data.

In some of the works considered here, the authors compared statistically the experimental database against the most important methods available in literature for the prediction of refrigerant heat transfer coefficients and pressure gradients; the comparisons were characterized by the following parameters:

$$\varepsilon_n = \left(\frac{g_{\text{pred},n} - g_{\text{exp},n}}{g_{\text{exp},n}}\right) \tag{1}$$

$$\bar{\varepsilon} = \frac{1}{N}\sum_{n=1}^{N}\varepsilon_n \tag{2}$$

$$|\bar{\varepsilon}| = \frac{1}{N}\sum_{n=1}^{N}|\varepsilon_n| \tag{3}$$

$$sd = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\varepsilon_n - \bar{\varepsilon})^2} \tag{4}$$

The results of the comparison obtained in each paper are summarized in Table 2 for the heat transfer coefficients and in Table 3 for the pressure gradients.

From Table 2 it can be observed that Shah (1976) correlation and Gungor and Winterton (1987) correlation were compared with five (Bredesen et al., 1997; Knudsen and Jensen, 1997; Sawant et al., 2003; Park and Hrnjak, 2007; Oh et al., 2008) and four (Bredesen et al., 1997; Yoon et al., 2004; Park and Hrnjak, 2007; Cho and Kim, 2007) independent databases, respectively: in all cases these correlations underpredicted the measured heat transfer coefficients. Gungor and Winterton (1986) method yielded good results only for the Park and Hrnjak (2007) database and overestimated strongly the data obtained by Zhao and Bansal (2007), even if Park and Hrnjak (2007) and Zhao and Bansal (2007) investigated similar inner diameter tube and saturation temperatures. Likewise the method of Liu and Winterton (1991) predicted carefully the values obtained by Zhao and Bansal (2007), but it did not estimate well the heat transfer coefficients furnished by Sawant et al. (2003), Yoon et al. (2004), Park and Hrnjak (2007), Cho and Kim (2007) and Oh et al. (2008). Kandlikar (1990) correlation underestimated meaningfully the databases of Yoon et al. (2004) and Oh et al. (2008), but predicted quite well the values measured by Cho and Kim (2007) and Zhao and Bansal (2007). Yoon et al. (2004) correlation, developed specifically for carbon dioxide, predicted satisfactory the data published by Cho and Kim (2007) and Zhao and Bansal (2007), but it underpredicted values of Koyama et al. (2004) with a mean absolute error up to 50%. Jung et al. (1989) method resulted as the best method because it granted good results if compared to the databases of Cho and Kim (2007), Zhao and Bansal (2007) and Oh et al. (2008), by Yoon et al. (2004) (it underestimated all the data except for those by Yoon et al. (2004)). All correlations that appear in Table 2 are empirical. Among phenomenological method we considered that by Cheng et al. (2008b) that is a flow pattern based heat transfer method developed for CO2 using 1124 experimental values available in literature measured in single circular channels and multi-channels with circular, triangular and rectangular cross-sections. The authors verified that their method was able to predict the entire database with an absolute mean error of 34% and the 71.4% of points within ±30%.

Even if the results reported in Table 2 were derived from the statistical comparison of the predictive methods with the entire experimental database, some remarks about their use in specified operating conditions can be furnished. Yun et al. (2003) compared the Gungor and Winterton (1986) correlation with the measured heat transfer coefficients data segregated by refrigerant mass flow rate: they noticed large deviations for the lower mass flux investigated, while for high mass fluxes they found a good agreement. This result is in accordance with the observations by Park and Hrnjak (2007): the Gungor and Winterton (1986) correlation tended to overpredict experimental data for a mass flux of 400 kg/m^2s and to underpredict them between 100 and 200 kg/m^2 s. Also Cheng et al. (2008b) compared their model with data segregated by flow regime; they observed that the predicted results in the dryout (191 points) and mist flow (160 points) regions were not satisfactory: in fact for the last two regimes, the model of Cheng et al. (2008b) provided a percentage of data less than 50% in an error band within ±30%.

Concerning the experimental databases analyzed in this article, it can be also noticed that all the considered predictive methods tended to underestimate the heat transfer coefficients published by Bredesen et al. (1997) and Koyama et al. (2004). Similar conclusions can be drawn for the experimental values measured by Park and Hrnjak (2007) and Oh et al. (2008). On the contrary the heat transfer coefficients

Table 1 – Experimental studies on flow boiling of pure CO_2 in horizontal circular macro-channels.

	Year of publication	Measured parameters	Channel material and orientation	Heating condition	$d_i/d_o/l$ (mm)	G ($kgm^{-2}s^{-1}$)	q (kWm^{-2})	t_{sat} (°C)	x	h_{min}/h_{max} ($kWm^{-2}K^{-1}$)	$(dp/dz)_{min}$ $/(dp/dz)_{max}$ ($kPam^{-1}$)
Bredesen et al. (1997)	1997	h, dp/dz	Aluminum horizontal smooth tube	Joule effect	7/10/2500	200, 300, 400	3, 6, 9	−25, −10, 5	0 ÷ 1	5/16	0.2/5
Knudsen and Jensen (1997)	1997	h	Stainless steel (type 316) horizontal smooth tube	Secondary fluid (R22)	10.06/30/1120	85, 125, 175	8, 13	−25, −10	0 ÷ 0.9	3.5/6	–
Yun et al. (2003)	2003	h	Stainless steel horizontal smooth tube	Joule effect	6.00/8.00/1400	170, 240, 320	10, 15, 20	5, 10	0.1 ÷ 0.9	3/15	–
Sawant et al. (2003)	2003	h	Stainless steel horizontal smooth tube	Secondary fluid (water)	8.0/9.5/–	250, 500, 650	24 ÷ 58	5, 10	0.1 ÷ 0.8	5/55	–
Yoon et al. (2004)	2004	h, dp/dz	Stainless steel (type 316) horizontal smooth tube	Joule effect	7.53/9.53/5000	212, 318, 424, 530	12.3, 16.4, 18.9	−4, 0, 5, 10, 15, 20	0 ÷ 0.7	3/13	1.5/6
Koyama et al. (2004)	2004	h, dp/dz	Copper horizontal smooth and micro-fin tube	Secondary fluid (water)	4.42/6.0/2064 (smooth tube) 4.90/6.02/2064 (micro-fin tube)	362 ÷ 650	–	−5.5 ÷ 14.3	0 ÷ 1	20/40	1.5/8
Hashimoto and Kiyotani (2004)	2004	h	Stainless steel horizontal smooth tube	Secondary fluid (water)	6.0/6.8/4000	161.9 ÷ 639.3	11.5 ÷ 38.6	0 ÷ 10	0.16 ÷ 1	40/70	–
Schael and Kind (2005)	2005	h	Nickel horizontal smooth tube and copper horizontal micro-fin tube	Joule effect	14/–/– (smooth tube) 8.62/9.52/200 (micro-fin tube)	75, 150, 250, 300, 500	2.1 ÷ 64.5	−10, 5	0.1 ÷ 0.9	2/50	–
Wu et al. (2005)	2005	h, dp/dz	Copper horizontal smooth tube	–	4/–/500	100 ÷ 300	2 ÷ 18	1 ÷ 15	0.1 ÷ 0.9	1.5/15	2.3/5
Hashimoto et al. (2006)	2006	h, dp/dz	Copper horizontal smooth tube	Secondary fluid (water)	5.2/6/3000, 4000, 5000	150, 270, 400, 520, 630	10 ÷ 40	0, 5, 10	–	1.5/70	1/10
Gao and Honda (2006)	2006	h	Stainless steel horizontal smooth tube	Joule effect	3/–/2185	236, 393, 590, 786, 1179	5, 10, 20, 30	−7, 0, 10	0.12 ÷ 1	1.5/16	–
Dang et al. (2006)	2006	h	Stainless steel (type 316) horizontal smooth tube	Joule effect	4, 6/–/–	360, 720, 1440	4.5, 9, 18, 36	15	0 ÷ 1	0.5/12	–
Park and Hrnjak (2007)	2007	h, dp/dz	Copper horizontal smooth tube	Secondary fluid (HFE 7100)	6.1/9.6/150	100, 200, 400	5, 10, 15	−30, −15	0.1 ÷ 0.8	3/9.5	0.5/10

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Table 1 (continued)

	Year of publication	Measured parameters	Channel material and orientation	Heating condition	$d_i/d_o/l$ (mm)	G ($kgm^{-2}s^{-1}$)	q (kWm^{-2})	t_{sat} (°C)	x	h_{min}/h_{max} ($kWm^{-2}K^{-1}$)	$(dp/dz)_{min}/(dp/dz)_{max}$ ($kPam^{-1}$)
Cho and Kim (2007)	2007	h, dp/dz	Horizontal smooth and micro-fin tube	Joule effect	4/5/5000 (smooth tube) 7.70/9.522/5000 (smooth tube) 4/5/5000 (micro-fin tube) 8.92/9.52/5000 (micro-fin tube)	212, 318, 424, 530, 656	6, 12, 16, 20	0, 5, 10, 20	0 ÷ 1	3/30	0.5/2.5
Zhao and Bansal (2007)	2007	h	Stainless steel horizontal smooth tube	Joule effect	4.57/6.35/4500	139.5 ÷ 230.9	12.6 ÷ 19.3	≈ −29	0.1 ÷ 1	4/7	–
Oh et al. (2008)	2007	h, dp/dz	Stainless steel horizontal smooth tube	Joule effect	7.75/9.53/5000	200, 300, 400, 500	10, 20, 30, 40	−5, 0, 5	0 ÷ 0.8	2/12	0.2/2.5

obtained by Zhao and Bansal (2007) were overestimated by correlations of Yoon et al. (2004), Gungor and Winterton (1986), Liu and Winterton (1991), Jung et al. (1989), Kattan et al. (1998) and Cooper (1984) and underpredicted only by the Kandlikar (1990) method.

With reference to the pressure gradients (Table 3) it can be noticed that the considered correlations tended to overestimate meaningfully all the experimental data reported in Table 1.The Müller-Steinhagen and Heck (1986) method was the only one that provided accurate results in comparison with the data by Park and Hrnjak (2007), while the data by Oh et al. (2008) and Bredesen et al. (1997) were quite well predicted from Cho et al. (1999) correlation and Fuchs (1975) method, respectively.

For the carbon dioxide data segregated by mass flow rate, Cho and Kim (2007) observed that the C coefficient method (Chisholm, 1983) predicted their data with an absolute mean error of 20% at low mass flux and up to 70% at high mass flux. Compared to the database of Oh et al. (2008), the Chisholm (1983) correlation predicted pressure drops higher than those measured, especially at the higher heat and mass fluxes. On the contrary Jung and Radermacher (1989) correlation and Friedel (1979) correlation overpredicted significantly the experimental values at lower heat and mass fluxes.

The correlations reported in Table 3 are empirical. Cheng et al. (2008a) collected a database (384 points) of CO_2 two-phase flow pressure drops from 5 works available in literature and compared the database to the leading empirical pressure drop methods (Yoon et al., 2004; Friedel, 1979; Grönnerud, 1979; Müller-Steinhagen and Heck, 1986; Chisholm, 1983; Moreno Quibén and Thome, 2007a; Moreno Quibén and Thome, 2007b). None of the methods considered was able to predict the CO_2 pressure drop data in a satisfactory way: in fact, except for the Friedel (1979) method, the methods provided a percentage of predicted points lower than 56% in an error band within ±30%.

Therefore, Cheng et al. (2008a) developed a new flow pattern based phenomenological model for frictional pressure drop during flow boiling of CO_2. It was able to predict the database better than the existing methods (74.7% of the entire database predicted within ±30%). Cheng et al. (2008a) compared their model also with data segregated by flow regime obtaining results similar to those found for the entire database.

From the above considerations, it can be deduced that in most cases the predictive methods tended to underestimate the experimental heat transfer coefficients, while the correlations considered for the prediction of the pressure gradients generally overpredicted the measured data. Probably it is due to the fact that the most of the methods considered were developed using experimental data for fluids with low reduced pressures at ordinary temperatures, while the carbon dioxide has higher vapor density, reduced pressure and thermal conductivity, lower surface tension and vapor viscosity than those of conventional refrigerants at the same evaporation temperature.

The results of this analysis suggest that there is a need for further experimental research and the development of suitable correlations for the boiling heat transfer and pressure drops of carbon dioxide or, more in general, for common fluids at reduced pressure similar to that of CO_2.

Table 2 – Results of statistical comparison among experimental and predicted values of pure CO_2 two-phase heat transfer coefficient obtained in each work described in Table 1.

	Bredesen et al. (1997)	Knudsen and Jensen (1997)	Yun et al. (2003)	Sawant et al. (2003)	Yoon et al. (2004)	Koyama et al. (2004)	Hashimoto and Kiyotani (2004)	Park and Hrnjak (2007)	Cho and Kim (2007)	Zhao and Bansal (2007)	Oh et al. (2008)
Yoon et al. (2004) correlation[a]					$\bar{\varepsilon} = 1.5\%$ $\lvert\bar{\varepsilon}\rvert = 15.2\%$ $sd = 21.1\%$	Underpredicts the experimental values with a mean absolute error up to 50%			$\bar{\varepsilon} = 20.39\%$ $sd = 14.23\%$	$\bar{\varepsilon} = 18.7\%$ $\lvert\bar{\varepsilon}\rvert = 21.7\%$	
Shah (1976) correlation	Underpredicts the experimental values	Underpredicts the experimental values		Predicts less than 40% of the data to within ±50% of the measured value with almost 100% of the data underpredicted				$\bar{\varepsilon} = -37.4\%$ $\lvert\bar{\varepsilon}\rvert = 43.2\%$			$\bar{\varepsilon} = -47.3\%$ $\lvert\bar{\varepsilon}\rvert = 49.0\%$
Gungor and Winterton (1987) correlation	Underpredicts the experimental values				$\bar{\varepsilon} = -21.2\%$ $\lvert\bar{\varepsilon}\rvert = 34.8\%$ $sd = 38.9\%$			$\bar{\varepsilon} = -39.2\%$ $\lvert\bar{\varepsilon}\rvert = 41.7\%$	$\bar{\varepsilon} = -20.91\%$ $sd = 4.28\%$		
VDI (1993) correlation	Underpredicts the experimental values										
Bonn and Steiner (1980) correlation	Underpredicts the experimental values										
Gungor and Winterton (1986) correlation			$-60\% \leq \bar{\varepsilon} \leq 18\%$ $10\% \leq \lvert\bar{\varepsilon}\rvert \leq 67\%$	Predicts 48% of the data to within ±50% of the measured value with 97% of the data underpredicted				$\bar{\varepsilon} = 1.74\%$ $\lvert\bar{\varepsilon}\rvert = 14.4\%$		$\bar{\varepsilon} = 53.2\%$ $\lvert\bar{\varepsilon}\rvert = 53.2\%$	$\bar{\varepsilon} = -32.4\%$ $\lvert\bar{\varepsilon}\rvert = 32.7\%$
Bennett and Chen (1980) correlation				Predicts 47% of the data to within ±50% of the measured value with 69% of the data underpredicted							
Chen (1966) correlation				Predicts less than 40% of the data to within ±50% of the measured value							

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Table 2 (*continued*)

	Bredesen et al. (1997)	Knudsen and Jensen (1997)	Yun et al. (2003)	Sawant et al. (2003)	Yoon et al. (2004)	Koyama et al. (2004)	Hashimoto and Kiyotani (2004)	Park and Hrnjak (2007)	Cho and Kim (2007)	Zhao and Bansal (2007)	Oh et al. (2008)
Liu and Winterton (1991) correlation				Predicts less than 40% of the data to within ±50% of the measured value	$\bar{\varepsilon} = 22.7\%$ $\lvert\bar{\varepsilon}\rvert = 44.7\%$ $sd = 76.1\%$			$\bar{\varepsilon} = -19.3\%$ $\lvert\bar{\varepsilon}\rvert = 24.3\%$	$\bar{\varepsilon} = -59.5\%$ sd = 6.2%	$\bar{\varepsilon} = 0.4\%$ $\lvert\bar{\varepsilon}\rvert = 9.2\%$	$\bar{\varepsilon} = 12.6\%$ $\lvert\bar{\varepsilon}\rvert = 32.6\%$
Hwang et al. (1997) correlation				Predicts 42% of the data to within ±50% of the measured value with 34% of the data underpredicted	$\bar{\varepsilon} = -24.7\%$ $\lvert\bar{\varepsilon}\rvert = 48.5\%$ $sd = 58.7\%$						
Jung et al. (1989) correlation					$\bar{\varepsilon} = 0.4\%$ $\lvert\bar{\varepsilon}\rvert = 37.1\%$ $sd = 48.3\%$				$\bar{\varepsilon} = -9.58\%$ $sd = 8.61\%$	$\bar{\varepsilon} = 12.3\%$ $\lvert\bar{\varepsilon}\rvert = 19.0\%$	$\bar{\varepsilon} = -14.3\%$ $\lvert\bar{\varepsilon}\rvert = 21.6\%$
Kandlikar (1990) correlation					$\bar{\varepsilon} = -33.9\%$ $\lvert\bar{\varepsilon}\rvert = 39.9\%$ $sd = 43.1\%$				$\bar{\varepsilon} = 10.5\%$ $sd = 6.3\%$	$\bar{\varepsilon} = -15.8\%$ $\lvert\bar{\varepsilon}\rvert = 16.8\%$	$\bar{\varepsilon} = -38.9\%$ $\lvert\bar{\varepsilon}\rvert = 39.2\%$
Yu et al. (1999) correlation						Underpredicts the experimental values with a mean absolute error up to 30%					
Yoshida et al. (1994) correlation							Does not estimate well the experimental trends and values				
Sun and Groll (2002) correlation[a]							Does not estimate well the experimental trends and values				
Wattelet et al. (1994) correlation								$\bar{\varepsilon} = -6.2\%$ $\lvert\bar{\varepsilon}\rvert = 18.3\%$			
Kattan et al. (1998) correlation										$\bar{\varepsilon} = 10.1\%$ $\lvert\bar{\varepsilon}\rvert = 41.6\%$	
Cooper (1984) correlation										$\bar{\varepsilon} = 11.5\%$ $\lvert\bar{\varepsilon}\rvert = 14.0\%$	

[a] Correlation developed specifically for carbon dioxide.

Table 3 – Results of statistical comparison among experimental and predicted values of pure CO_2 two-phase pressure gradient obtained in each work described in Table 1.

	Bredesen et al. (1997)	Yoon et al. (2004)	Park and Hrnjak (2007)	Cho and Kim (2007)	Oh et al. (2008)
Yoon et al. (2004) correlation[a]		$\bar{\varepsilon} = 1.8\%$; $\lvert\bar{\varepsilon}\rvert = 16.2\%$			
Fuchs (1975) correlation	Estimates satisfactorily pressure gradients				
Chisholm (1983) correlation		B coefficient method: $\lvert\bar{\varepsilon}\rvert = 87\%$; C coefficient method: $\lvert\bar{\varepsilon}\rvert = 125.9\%$		C coefficient method: $20\% \leq \lvert\bar{\varepsilon}\rvert \leq 70\%$	$\bar{\varepsilon} = 43.3\%$; $\lvert\bar{\varepsilon}\rvert = 43.3\%$
Jung and Radermacher (1989) correlation		$\lvert\bar{\varepsilon}\rvert = 128.9\%$			$\bar{\varepsilon} = 41.3\%$; $\lvert\bar{\varepsilon}\rvert = 41.3\%$
Friedel (1979) correlation			$\bar{\varepsilon} = 22.8\%$; $\lvert\bar{\varepsilon}\rvert = 32.5\%$		$\bar{\varepsilon} = 41.2\%$; $\lvert\bar{\varepsilon}\rvert = 41.2\%$
Grönnerud (1979) correlation			$\bar{\varepsilon} = 53.9\%$; $\lvert\bar{\varepsilon}\rvert = 56.4\%$		
Müller-Steinhagen and Heck (1986) correlation			$\bar{\varepsilon} = -5.3\%$; $\lvert\bar{\varepsilon}\rvert = 19.2\%$		
Lockhart and Martinelli (1949) correlation			$\bar{\varepsilon} = 113\%$; $\lvert\bar{\varepsilon}\rvert = 115\%$		
Chisholm (1973) correlation			$\bar{\varepsilon} = 76.3\%$; $\lvert\bar{\varepsilon}\rvert = 78.3\%$		
Chisholm (1968) correlation					$\bar{\varepsilon} = 39.6\%$; $\lvert\bar{\varepsilon}\rvert = 39.6\%$;
Cho et al. (1999) correlation					$\bar{\varepsilon} = 13.9\%$; $\lvert\bar{\varepsilon}\rvert = 19.5\%$
Cheng et al. (2008a)[a]	Predicts 81.5% of the data to within ± 30% of the measured value				

a Correlation developed specifically for carbon dioxide.

3. Experimental results

The experimental results from University of Naples were obtained by an experimental plant which schematic is shown in Fig. 1.

A detailed description of the test facility, the data acquisition system, the measurement equipment and the data reduction procedure is reported in (Mastrullo et al., 2009a). The choice of the experimental plant instruments was based on an a-priori analysis of measurement errors and equipment cost (Mastrullo et al., 2008).

Preliminarily to the evaluation of carbon dioxide flow boiling heat transfer coefficients and pressure gradients, several tests were carried out to check the accuracy and repeatability of the measurements and the consistency with the hypotheses for the data reduction (Mastrullo et al., 2009a).

The two-phase characteristics of pure R744 were investigated in a seamless stainless steel, smooth, horizontal, circular tube with inner diameter of 6.00 mm for a wide range of operating conditions; 217 values of the local heat transfer coefficient and 118 values of local pressure gradient were obtained. The ranges corresponding to each test are specified in Table 4 for the refrigerant mass flux, the saturation temperature, the heat flux and the vapor quality.

The measurement uncertainty was evaluated accordingly to the single-sample analysis suggested by Moffat (1988): it ranged between 3.4% and 6.5% for the local heat transfer coefficient and between 0.2% and 2.4% for the local pressure gradient.

The experiments allowed to evaluate the dependence of heat transfer coefficients and pressure gradients on vapor quality, saturation temperature, refrigerant mass flux and heat flux.

Table 4 – The experimental operating conditions.

G (kgm^{-2}s^{-1})	p_{sat} (bar)	t_{sat} (°C)	q (kWm^{-2})	Δx_{exp}
200	28.2	−7.8	10.1	0.12 ÷ 0.98
200	39.7	5.0	20.3	0.27 ÷ 0.96
201	39.7	5.0	15.2	0.41 ÷ 0.88
202	38.9	4.2	10.1	0.13 ÷ 0.96
203	32.0	−3.2	10.1	0.13 ÷ 0.94
250	28.2	−7.8	10.1	0.09 ÷ 0.82
251	32.0	−3.2	10.1	0.09 ÷ 0.75
252	40.4	5.7	10.2	0.07 ÷ 0.93
297	32.1	−3.1	10.1	0.07 ÷ 0.88
300	39.7	5.0	20.2	0.17 ÷ 0.85
300	40.5	5.8	10.3	0.09 ÷ 0.85
301	28.2	−7.8	10.1	0.07 ÷ 0.97
302	39.7	5.0	15.5	0.25 ÷ 0.86
348	28.3	−7.7	20.0	0.18 ÷ 0.78
348	39.7	5.0	10.0	0.02 ÷ 0.93
348	39.7	5.0	20.6	0.30 ÷ 0.88
349	28.2	−7.8	10.1	0.10 ÷ 0.76
349	32.0	−3.2	10.1	0.05 ÷ 0.78

They showed that the heat transfer coefficients is nearly independent of mass velocity and, for low and medium evaporating temperatures, of vapor quality. The influence of evaporating temperature was remarkable only for low vapor quality. A meaningful influence of the heat flux on the heat transfer coefficients for all values of vapor quality was also observed (Mastrullo et al., 2009a, 2009b).

Concerning the R744 pressure gradients, we measured values increasing with vapor quality until a maximum was reached. The increase of the saturation temperature strongly influenced pressure gradients, mainly due to the increase in the vapor density of the mixture and the decrease in mean velocity. For the opposite reason the increase of the mass flow rate, for fixed thermodynamic properties, increased the pressure gradients.

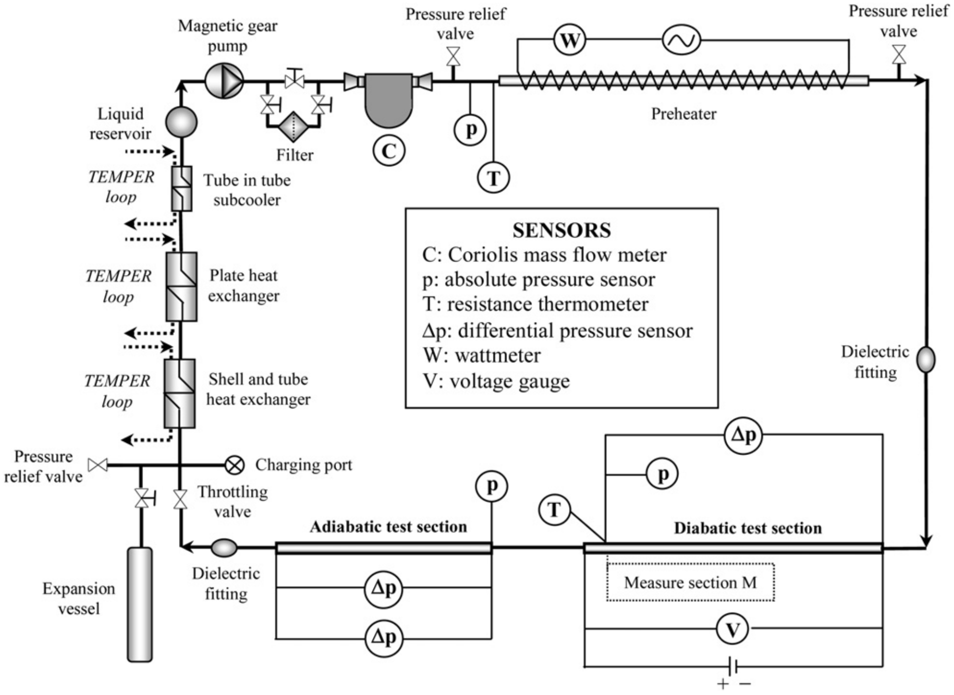

Fig. 1 – Experimental apparatus scheme.

Heat transfer coefficients and pressure gradients measured in that study were compared with those obtained by Yun et al. (2003), Yoon et al. (2004), Cho and Kim (2007) and Oh et al. (2008), since they ran experiments on test sections with similar inner diameters and operating conditions. All the authors drew experimental trends of heat transfer coefficient and pressure gradients comparable to those observed in our laboratory (Mastrullo et al., 2009a). Also concerning the absolute values for the experimental results, a good agreement was observed in most cases, even if some discrepancies were found about the heat transfer coefficients (Mastrullo et al., 2009a).

4. Comparison of experimental heat transfer coefficients with existing correlations

In the following the measured data are compared statistically with some of the most important correlations available in literature in order to establish the best predictive method for the R744 heat transfer coefficients and pressure gradients in the ranges of operating conditions investigated.

The measured values of pure CO_2 heat transfer coefficient were compared with the correlations by Yoon et al. (2004), Shah (1976), Gungor and Winterton (1987), Gungor and Winterton (1986), Cheng et al. (2008b), Jung et al. (1989), Steiner and Taborek (1992), Panek (1992), Bandarra Filho et al. (1997) and Bandarra Filho (1997). The predictive methods of Cheng et al. (2008b) and Yoon et al. (2004) were developed specifically for carbon dioxide, while the other correlations were obtained starting from experiments with low and medium pressure refrigerants.

The comparison was made both for the whole database and the data segregated by flow regime (annular and intermittent) by means of the flow pattern map by Cheng et al. (2008a).

In order to evaluate the reliability of the predictive methods, a statistical analysis was run. At this scope the parameters defined by equations (2)–(4) were evaluated; the percentage of points inside an error window of ±30% was also calculated. The mean error returns a value equal to zero for a symmetric distribution, i.e. when the experimental data are equally overestimated and underestimated; it is positive when the mean of the predictions are conservative with respect to the experimental data. The standard deviation is calculated to measure the scatter of the data distribution.

The results of the comparison are reported in Table 5.

For the entire database, it can be observed that all correlations, except those of Gungor and Winterton (1986), Cheng et al. (2008b) and Yoon et al. (2004), tended to

Table 5 – Results of statistical comparison between the predicted and the experimental R744 heat transfer coefficients.

	Number of experimental points	Predictive methods	$\bar{\varepsilon}$ (%)	$\lvert\bar{\varepsilon}\rvert$ (%)	*sd* (%)	λ (%)
Whole database	217	Yoon et al. (2004)[a]	30.9	31.3	19.9	52.5
		Shah (1976)	−43.4	43.6	16.2	14.7
		Gungor and Winterton (1987)	−33.9	34.0	12.2	35.0
		Gungor and Winterton (1986)	22.7	24.7	19.8	63.1
		Cheng et al. (2008a)[a]	4.7	22.6	30.4	75.6
		Jung et al. (1989)	−13.9	21.6	20.1	76.0
		Steiner and Taborek (1992)	−19.4	23.7	18.9	67.3
		Panek (1992)	−47.0	47.1	18.1	17.5
		Bandarra Filho et al. (1997)	−42.9	43.2	20.1	24.9
		Bandarra Filho (1997)	−41.7	41.8	16.5	23.0
Intermittent flow regime	24	Yoon et al. (2004)[a]	3.2	3.2	9.9	81.1
		Shah (1976)	−8.1	8.1	21.4	75.1
		Gungor and Winterton (1987)	−3.7	3.7	10.4	81.1
		Gungor and Winterton (1986)	4.0	4.1	12.7	79.3
		Cheng et al. (2008a)[a]	4.4	4.4	12.6	79.3
		Jung et al. (1989)	−0.5	1.9	5.9	85.7
		Steiner and Taborek (1992)	−4.2	4.2	11.3	79.3
		Panek (1992)	−4.7	4.7	13.4	79.3
		Bandarra Filho et al. (1997)	−3.5	3.5	10.9	81.1
		Bandarra Filho (1997)	−3.9	3.9	11.1	80.6
Annular flow regime	152	Yoon et al. (2004)[a]	19.9	20.2	20.1	70.0
		Shah (1976)	−28.8	29.1	22.6	40.1
		Gungor and Winterton (1987)	−23.0	23.1	18.1	56.2
		Gungor and Winterton (1986)	13.9	15.7	17.6	77.4
		Cheng et al. (2008a)[a]	8.6	10.3	13.3	93.1
		Jung et al. (1989)	−12.8	16.1	17.0	80.2
		Steiner and Taborek (1992)	−13.6	17.1	18.9	75.6
		Panek (1992)	−30.5	30.6	24.3	42.9
		Bandarra Filho et al. (1997)	−27.8	28.1	23.5	48.4
		Bandarra Filho (1997)	−26.7	26.8	20.7	47.0

[a] Correlation developed specifically for carbon dioxide.

underpredict the experimental data. Jung et al. (1989) method provided the lowest absolute mean error (21.6%) and was able to predict 76.0% of data within ±30% error window. This was in agreement with the results obtained from the literature survey: in fact, as can be drawn from Table 2, Jung et al. (1989) correlation furnished reliable predictions also for the databases of Cho and Kim (2007), Zhao and Bansal (2007) and Oh et al. (2008). The methods

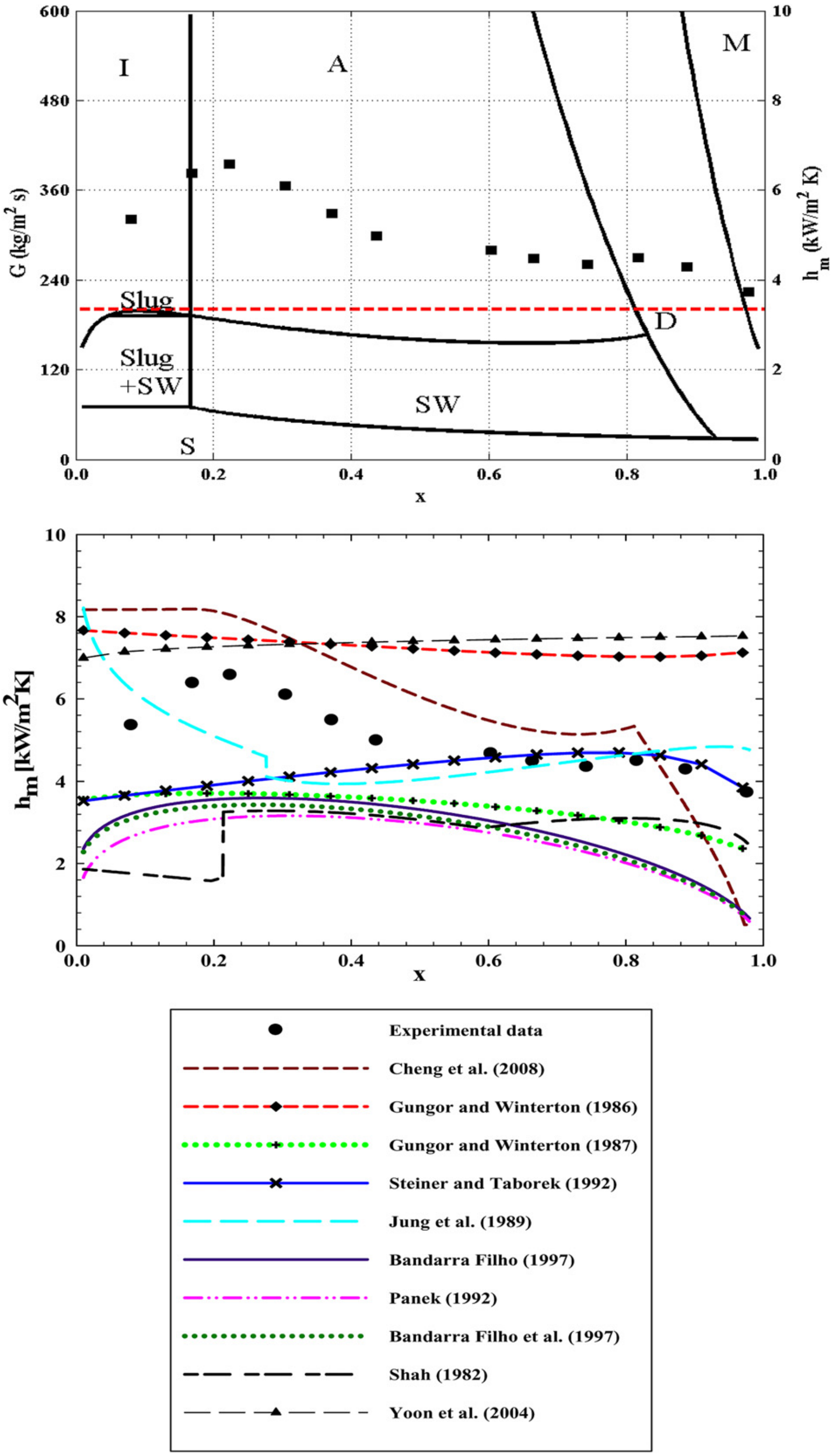

Fig. 2 – Flow pattern map and direct comparison of the experimental heat transfer coefficients against predicted values for $G = 201$ kg/m^{2}s, $t_{sat} = 4.2$ °C and $q = 9.6$ kW/m^2.

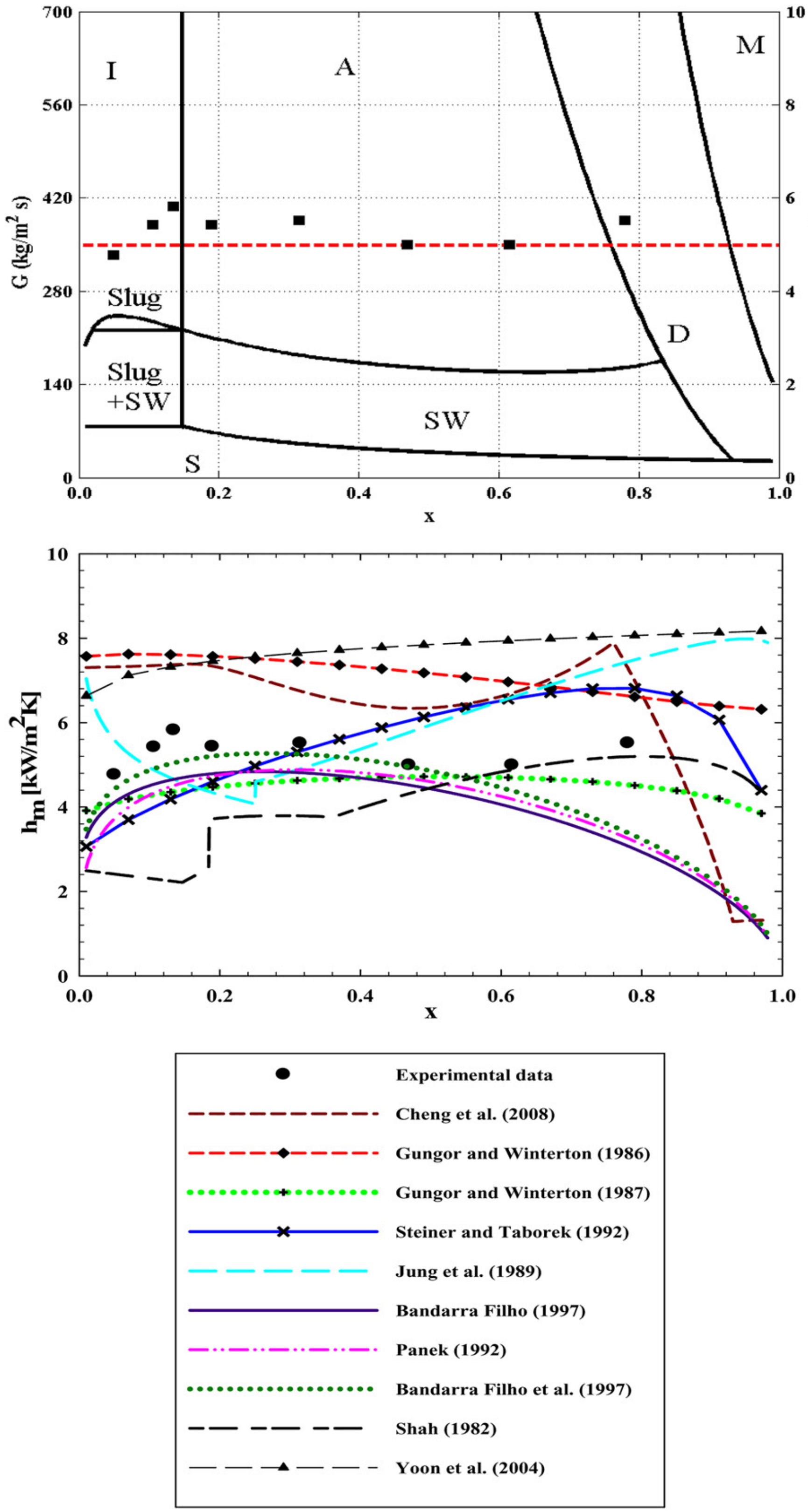

Fig. 3 – Flow pattern map and direct comparison of the experimental heat transfer coefficients against predicted values for $G = 349\ \mathrm{kg/m^2s}$, $t_{sat} = -3.2\ ^\circ\mathrm{C}$ and $q = 10.1\ \mathrm{kW/m^2}$.

of Shah (1976), Gungor and Winterton (1987), Panek (1992), Bandarra Filho et al. (1997) and Bandarra Filho (1997) diverted considerably from the measured data: in fact they supplied values of λ lower than 40%. The correlation of Yoon et al. (2004) did not allow to obtain satisfactory predictions even if it was developed specifically for carbon dioxide. On the basis of these results, from Table 2 it can be highlighted that the correlations of Shah (1976) and Gungor and Winterton (1987) underestimated all the experimental databases considered for the comparison.

However the above considerations were affected by data distribution with respect to the flow regimes; in fact, the analysis for each flow regime showed different results.

In the intermittent region, all the methods granted reliable predictions with a mean absolute error always lower than 8.1% and a percentage of points inside an error window of ±30% always higher than 75.1%. Results by Cheng et al. (2008b) correlation were the best in the annular flow regime both for absolute mean error (10.3%) and standard deviation (13.3%); besides, this method predicted 93.1% of data within ±30% error window, while for Yoon et al. (2004) correlation results $\lambda = 70.0\%$.

To overcome the limits of the statistical analysis, a further step was to evaluate how well the predictive methods captured the trends of heat transfer coefficients; for this reason a direct comparison was carried out. To highlight the main results of the comparison, Figs. 2 and 3 depict two examples of the flow pattern map, the plots of experimental and predicted data in some representative operating conditions.

From the comparison, it can be observed that only the model by Cheng et al. (2008b) was able to follow carefully the experimental trends. However in contrast with the predictions by Cheng et al. (2008b) correlation, in our experiments we did not observe an abrupt fall off of heat transfer coefficients for high vapor quality due to the dryout. It was due to the fact that in our plant the heating power is transferred to the fluid by Joule effect and, therefore, it was not possible to obtain dryout inception in steady state conditions. Besides, in the intermittent region, the method of Cheng et al. (2008b) predicted a heat transfer coefficient constant with the vapor quality, while we measured values of h_m increasing with the vapor quality (Fig. 2). Finally, as showed in Fig. 3, it can be noticed that the correlation of Cheng et al. (2008b) tended to overestimate the experimental data for high refrigerant mass fluxes.

Besides it can be noticed that the methods of Gungor and Winterton (1987), Gungor and Winterton (1986) and Yoon et al. (2004) predicted heat transfer coefficients almost constant at varying the vapor quality: this trend could be a good approximation of the measured values at medium vapor qualities and low–medium temperatures.

However the method of Gungor and Winterton (1987) provided satisfactory predictions only for high mass flux and low heat flux, while underestimated the experimental values in the other operating conditions investigated. The correlations of Gungor and Winterton (1986) and Yoon et al. (2004) tended to overpredict the measured heat transfer coefficients mainly for high vapor qualities and low heat fluxes. Similar deviations among experimental and predicted values for the Gungor and Winterton (1986) method over the whole range of refrigerant mass flux investigated can be observed, differently from that observed by Yun et al. (2003) and Park and Hrnjak (2007).

5. Comparison of experimental pressure gradients with existing correlations

The measured values of pure CO_2 pressure gradients were compared with the correlations by Yoon et al. (2004), Jung and Radermacher (1989), Friedel (1979), Grönnerud (1979), Müller-Steinhagen and Heck (1986) and Cheng et al. (2008a). The

Table 6 – Results of statistical comparison between the predicted and the experimental R744 pressure gradients.

	Number of experimental points	Predictive methods	$\bar{\varepsilon}$(%)	$\bar{\varepsilon}$|(%)	*sd* (%)	λ (%)
Whole database	125	Yoon et al. (2004)[a]	−3.8	56.4	66.0	18.4
		Jung and Radermacher (1989)	78.4	98.2	94.0	22.4
		Friedel (1979)	−13.4	23.3	26.4	70.4
		Grönnerud (1979)	4.2	49.0	54.9	26.4
		Müller-Steinhagen and Heck (1986)	−30.3	31.6	26.0	51.2
		Cheng et al. (2008b)[a]	0.6	44.4	49.9	28.8
Intermittent flow regime	22	Yoon et al. (2004)[a]	−11.7	11.7	26.3	64.8
		Jung and Radermacher (1989)	−7.6	8.0	20.5	68.8
		Friedel (1979)	−6.3	7.0	17.6	69.6
		Grönnerud (1979)	−10.2	10.2	23.4	65.6
		Müller-Steinhagen and Heck (1986)	−9.8	9.8	22.8	66.4
		Cheng et al. (2008b)[a]	−9.8	9.8	23.4	66.4
Annular flow regime	85	Yoon et al. (2004)[a]	−0.8	35.6	46.1	42.4
		Jung and Radermacher (1989)	75.9	80.5	85.3	40.8
		Friedel (1979)	−6.1	14.7	20.6	82.4
		Grönnerud (1979)	12.0	35.8	45.4	46.4
		Müller-Steinhagen and Heck (1986)	−20.4	20.6	22.3	66.4
		Cheng et al. (2008b)[a]	6.0	30.1	39.3	51.2

[a] Correlation developed specifically for carbon dioxide.

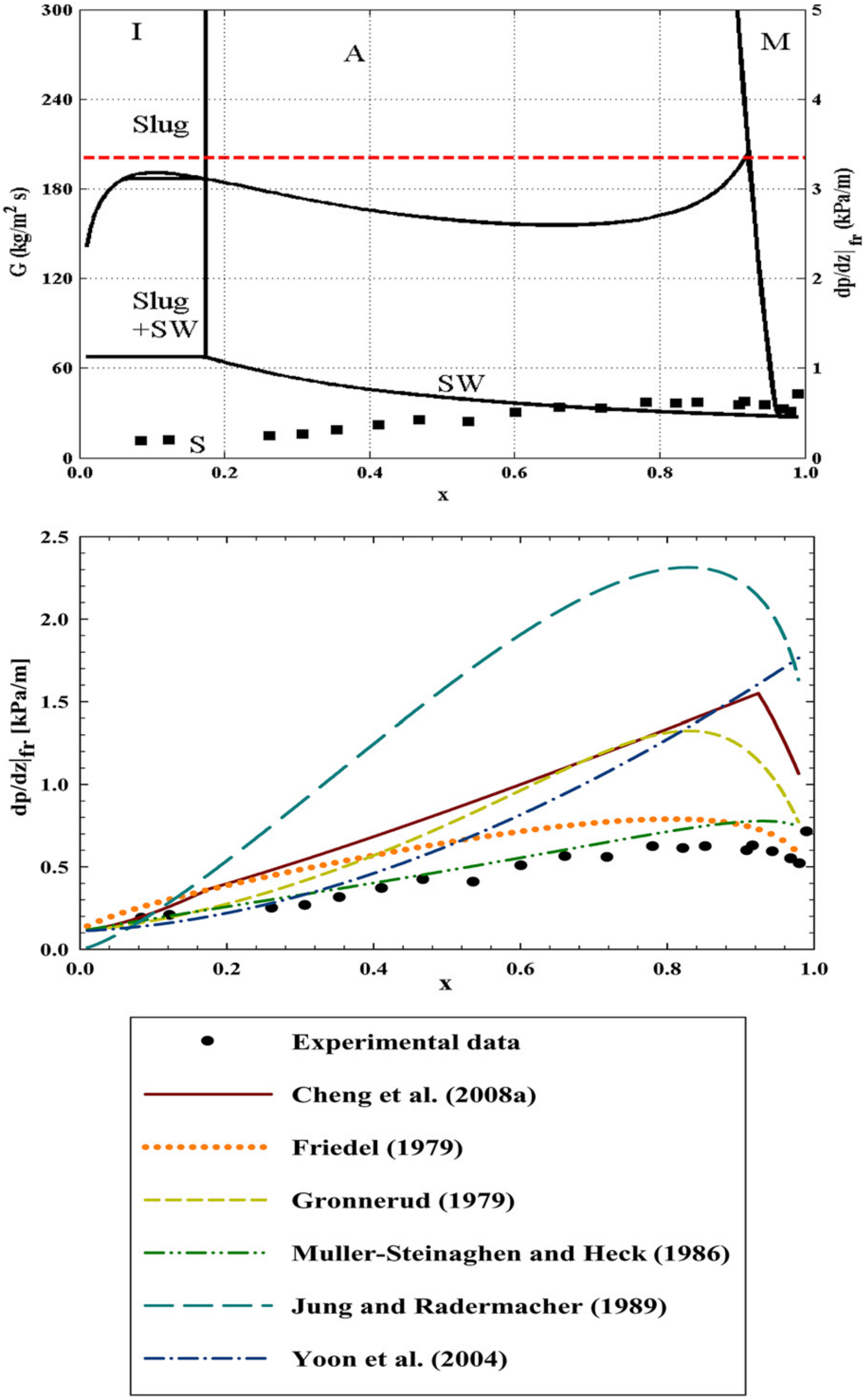

Fig. 4 – Flow pattern map and direct comparison of the experimental heat transfer coefficients against predicted values for $G = 201$ kg/m^{2}s and $t_{sat} = 5.0$ °C.

predictive methods of Cheng et al. (2008a) and Yoon et al. (2004) were developed specifically for carbon dioxide, while the other correlations were obtained starting from experiments with low and medium pressure refrigerants.

The results of the comparison are reported in Table 6.

For the entire database, it can be noticed that none of the correlations considered predicted carefully the experimental data. The method by Friedel (1979) was the only one able to estimate 70.4% of measured values with a mean absolute error lower than 30%. The correlations of Yoon et al. (2004), Jung and Radermacher (1989), Grönnerud (1979) and Cheng et al. (2008a) provided values of λ even lower than 30%, with a mean absolute error between 44.4% and 98.2%.

The analysis for segregated data by flow regimes showed similar results.

In the intermittent region, all methods estimated less than 70% of points within ±30%. However the lower values of $\bar{\varepsilon}$, $|\bar{\varepsilon}|$ and sd and the higher value of λ was granted by the

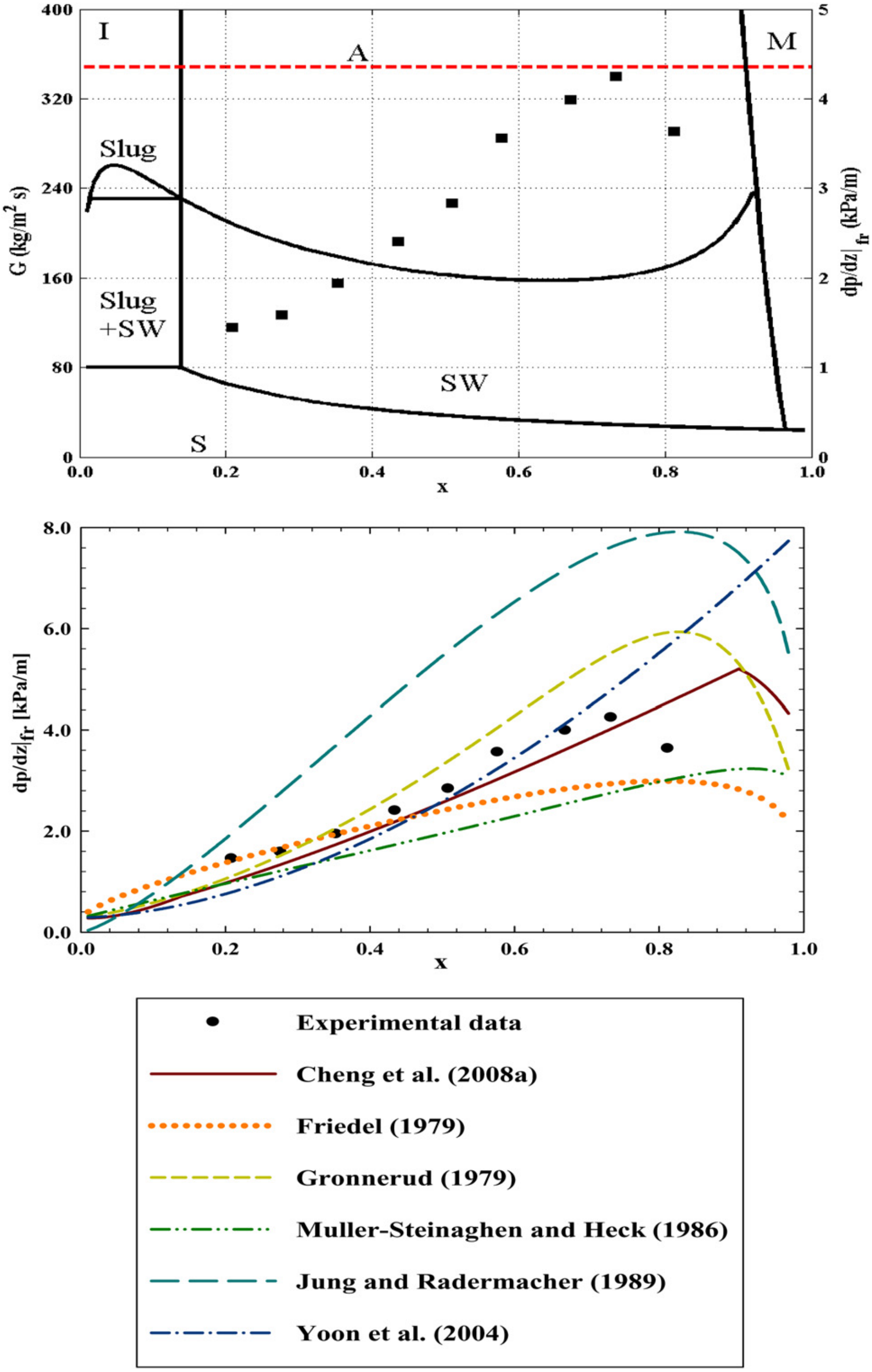

Fig. 5 – Flow pattern map and direct comparison of the experimental heat transfer coefficients against predicted values for $G = 349$ kg/m²s, $t_{sat} = -7.8$ °C and $q = 10.1$ kW/m².

correlation of Friedel (1979). Also in the annular region, results by Friedel (1979) correlation were the best both for absolute mean error (14.7%), standard deviation (20.6%) and percentage of points inside an error window of ±30% (82.4%) The methods of Yoon et al. (2004), Jung and Radermacher (1989), Grönnerud (1979) and Cheng et al. (2008a) provided values of λ even lower than 50%, with an absolute mean error between 30.1% and 80.5% and a standard deviation higher than 39%.

As for the heat transfer coefficients, also for the pressure gradients a direct comparison between predicted and experimental trends was carried out for all the operating conditions investigated. Two examples of a direct comparison are shown in Figs. 4 and 5.

From the analysis some general conclusions came out:

- For refrigerant mass fluxes lower than 350 kg/m^{2}s, the correlation of Müller-Steinhagen and Heck (1986) was able to predict carefully the experimental trends; good results were also provided by the method of Friedel (1979);
- For vapor qualities higher than 50% and a refrigerant mass flux equal to 350 kg/m^{2}s, the most accurate predictions were given by the correlation of Cheng et al. (2008a);
- The model of Müller-Steinhagen and Heck (1986) provided the best predictions of the vapor quality corresponding to the peak of the experimental pressure gradient.

6. Conclusions

In this paper the results of a statistical comparison between measured and predicted values of CO_2 heat transfer coefficients and pressure gradients during flow boiling in macrochannels currently available in literature were summarized. From the analysis carried out, it was observed that all the predictive methods tended to underpredict the experimental values for heat transfer and to overestimate the measured data for pressure drops.

Besides the heat transfer coefficients and pressure gradients measured in our laboratory (Mastrullo et al., 2009a, 2009b) were statistically compared with some of the most quoted correlations available in literature. The comparison was made both for the whole database and the data segregated by flow regimes (annular and intermittent) by means of the flow pattern map by Cheng et al. (2008a) developed specifically for CO_2.

Concerning the entire database of R744 heat transfer coefficients, we observed that the most of the correlations underpredicted the experimental data. Predictions by Jung et al. (1989) and Cheng et al. (2008b) correlations were the best. In fact the Jung et al. (1989) method provided the lowest mean absolute error (21.6%), estimated 76.0% of data within ±30% error window. Cheng et al. (2008b) method was the only one able to predict carefully the experimental trends.

Consequently to this analysis the suggestions for possible improvements of the best methods are to modify the method by Jung et al. (1989) with respect to the capture of the influence of the vapor quality on heat transfer coefficients and to set the influence of mass flow rate at high mass fluxes for Cheng et al. (2008b) method.

For the entire database of CO_2 pressure gradients it can be noticed that none of the predictive methods considered in this work predicted carefully the experimental data. The method of Friedel (1979) was the only one able to estimate 70.4% of measured values with a mean absolute error lower than 30%. For refrigerant mass fluxes lower than 350 kg/m^{2}s, the correlation of Müller-Steinhagen and Heck (1986) was able to predict carefully the experimental trends. For vapor qualities higher than 50% and a refrigerant mass flux near 350 kg/m^{2}s, the most accurate predictions were given by the correlation of Cheng et al. (2008a). The model by Müller-Steinhagen and Heck (1986) provided the best predictions of the vapor quality corresponding to the peak of the experimental pressure gradient.

In the future some effort should be made to get better predictions of pressure gradients mainly for high vapor qualities and refrigerant mass fluxes.

In order to improve the database available in the literature for CO_2 heat transfer coefficients and pressure gradients, next experimental works are recommended to address mainly dryout and mist flow regions, since a limited number of data points covering these flow patterns is available in literature.

REFERENCES

Bandarra Filho, E.P., Saiz Jabardo, J.M., Lima, C.U.S. Estudo da Transferência de Calor em Ebulição Convectiva de Refrigerantes em Tubos Horizontais. III Congreso Iberoamericano de Ingeniería Mecánica, La Habana, Cuba, 1997.

Bandarra Filho, E.P. Estudo da Transferência de Calor em Ebulição Convectiva de Refrigerantes Halogenados em Tubos Horizontais. Dissertação (Mestrado), Escola de Engenharia de São Carlos, Universidade de São Paulo, 1997.

Bennett, D.L., Chen, J.C., 1980. Forced convective boiling in vertical tubes for saturated pure components and binary mixtures. AIChE Journal 26, 454–461.

Bonn, D., Steiner, W., 1980. Ueber die Auswirkungen der Ungleichverteilung des Warmeübergangs am Rohrumfang bei der Verdampfung im durcströmten waagerechten Rohr, pp. 265–274. Wärme-und Stoffübertragung S.

Bredesen, A.M., Hafner, A.H., Pettersen, J., Nekså, P., Aflekt, K., 1997. Heat Transfer and Pressure Drop for in Tube Evaporation of CO_2. IIF-IIR-Commission B1, with E1 & E2, College Park.

Cavallini, A., Zilio C. Carbon dioxide as a natural refrigerant. In: 5th International Congress on Sustainable Energy Technologies. Vicenza, Italy, August 30–September 1, 2006.

Chen, J.C., 1966. A correlation for boiling heat transfer to saturated fluids in vertical flow. Industrial & Engineering Chemistry Process Design and Development 5, 322–339.

Cheng, L., Ribatski, G., Moreno Quibén, J., Thome, J.R., 2008a. New prediction methods for CO_2 evaporation inside tubes: part I – A two-phase flow pattern map and a flow pattern based phenomenological model for two-phase flow frictional pressure drops. Int. J. Heat and Mass Transfer 51, 111–124.

Cheng, L., Ribatski, G., Thome, J.R., 2008b. New prediction methods for CO_2 evaporation inside tubes: part II – an updated general flow boiling heat transfer model based on flow patterns. Int. J. Heat and Mass Transfer 51, 125–135.

Chisholm, D., 1968. The Influence of Mass Velocity on Friction Pressure Gradients during Steam–Water Flow. Thermodynamics and Fluid Mechanics Convection of the Institute of Mechanical Engineer, Bristol, UK.

Chisholm, D., 1973. Pressure gradients due to friction during the flow of evaporating two-phase mixtures in smooth tubes and channels. Int. J. Heat and Mass Transfer 16, 347–358.

Chisholm, D., 1983. Two-phase Flow in Pipelines and Heat Exchangers. Longman.

Cho, J.M., Kim, M.S., 2007. Experimental studies on the evaporative heat transfer and pressure drop of CO_2 in smooth and micro-fin tubes of the diameters of 5.00 and 9.52 mm. Int. J. Refrigeration 30, 984–986.

Cho, J.Y., Kedzierski, A.M., Domanski, P.A., 1999. A Generalized Pressure Drop Correlation for Boiling and Condensation of Alternative Refrigerants in Smooth Tube and Micro-fin Tube. 6333. NISTIR.

Cooper, M.G., 1984. Heat flow rates in saturated nucleate pool boiling a wide-range examination using reduced properties. Advanced Heat Transfer 16, 157–239.

Dang, C., Haraguchi, N., Yamada T., Hihara E. Effect of lubricating oil on boiling heat transfer of carbon dioxide. In: 7th IIR Gustav Lorentzen Conference on Natural Working Fluids, Trondheim, Norway, 2006. Directive 2006/40/EC, 2006.

Ducoulombier, M., Colasson, S., Haberschill, P. A Review on Carbon Dioxide Heat Transfer Characteristics during Flow Boiling. In: 8th IIR Gustav Lorentzen Conference on Natural Working Fluids, Copenhagen, Denmark, September 7–10, 2008.

Friedel, L. Improved friction drop correlations for horizontal and vertical two-phase pipe flow. In: European Two-phase Flow Group Meeting, paper E2, Ispra, Italy, 1979.

Fuchs, P.H. Trykkfall og varmeovergang ed strømning av fordampende væske i horisontale rør og bend, Dr. Lic. grad, Department of Refrigeration, NTH, Trondheim, Norway, 1975.

Gao, L., Honda, T. Flow and heat transfer characteristics of refrigerant and PAG oil in the evaporator of a CO_2 heat pump system. In: 7th IIR Gustav Lorentzen Conference on Natural Working Fluids, Trondheim, Norway, 2006.

Grönnerud, R., 1979. Investigation of Liquid Hold-up, Flow-resistance and Heat Transfer in Circulation Type of Evaporators, Part IV: Two-phase Flow Resistance in Boiling Refrigerants. Annexe 1972-1. Bullettin de l'Institute du Froid.

Gungor, K.E., Winterton, R.H.S., 1986. A general correlation for flow boiling in tubes and annuli. Int. J. Heat and Mass Transfer 29, 351–358.

Gungor, K.E., Winterton, R.H.S., 1987. Simplified general correlation for saturated flow boiling and comparison of correlation with data. Chemical Engineering Research and Design 65, 148–156.

Hafner, A., Nekså, P., April 13–15, 2004. Life Cycle Climate Performance (LCCP) of Mobile Air-Conditioning Systems with HFC-134a, HFC-152a and R744. MAC Summit, Washington DC.

Hashimoto, K., Kiyotani, A. Experimental Study of Pure CO_2 Heat Transfer during Flow Boiling inside Horizontal Tubes. In: Natural Working Fluids 2004: 6th IIR – Gustav Lorentzen Conference on Natural Working Fluids, Glasgow, UK, 2004.

Hashimoto, K., Kiyotani, A., Sasaki, N. Experimental study of influence of heat flux and mass velocity on carbon dioxide flow boiling heat transfer coefficient in horizontal smooth tube. In: 7th IIR Gustav Lorentzen Conference on Natural Working Fluids, Trondheim, Norway, 2006.

Hwang, Y., Kim, B.H., Radermacher, R. Boiling heat transfer correlation for carbon dioxide. In: International Conference on Heat Transfer Issues in Natural Refrigerants. University of Maryland, USA, 1997.

Jung, D.S., Radermacher, R., 1989. Prediction of pressure drop during horizontal annular flow boiling of pure and mixed refrigerants. Int. J. Heat and Mass Transfer 32, 2435–2446.

Jung, D.S., Radermacher, R., McLinden, M., Didion, D., 1989. A study of flow boiling heat transfer with refrigerant mixtures. Int. J. Heat and Mass Transfer 32, 1751–1764.

Kandlikar, S.G., Grande, W.J., 2003. Evolution of microchannel flow passages-thermohydraulic performance and fabrication technology. Heat Transfer Engineering 24, 3–17.

Kandlikar, S.G., 1990. A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes. Journal of Heat Transfer 112, 219–228.

Kattan, N., Thome, J.R., Favrat, D., 1998. Flow boiling in horizontal tubes: part 3-development of a new heat transfer model based on flow pattern. Int. J. Heat and Mass Transfer 120, 156–165.

Kim, M.-H., Pettersen, J., Bullard, C.W., 2004. EC Regulation 2037/2000, 2000, Fundamental process and system design issues in CO_2 vapor compression systems. Progress in Energy and Combustion Science 30, 119–174.

Knudsen, H.J., Jensen, P.H., 1997. Heat transfer coefficient for boiling carbon dioxide. In: Workshop Proceedings of CO_2 Technologies in Refrigeration, Heat Pumps and Air Conditioning Systems, Trondheim, Norway, 1997.

Koyama, S., Lee, S.M., Ito, D., Kuwahara, K., Ogawa, H. Experimental Study on Flow Boiling of Pure CO_2 and CO_2-Oil Mixtures inside Horizontal Smooth and Micro-fin Copper Tubes. In: Natural Working Fluids 2004: 6th IIR – Gustav Lorentzen Conference on Natural Working Fluids, Glasgow, UK, 2004.

Liu, Z., Winterton, R.H.S., 1991. A general correlation for saturated and subcooled flow boiling in tubes and annuli based on a nucleate pool boiling equation. Int. J. Heat and Mass Transfer 34, 2759–2766.

Lockhart, R.W., Martinelli, R.C., 1949. Proposed correlation of data for isothermal two-phase two-component flow in pipes. Chemical Engineering Progress 45, 39–45.

Mastrullo, R., Rosato, A., Vanoli, G.P., Thome, J.R., 2008. A methodology to select the experimental plant instrumentation based on an a priori analysis of measurement errors and instrumentation cost. International Communications in Heat and Mass Transfer 35, 689–695.

Mastrullo, R., Mauro, A.W., Rosato, A., Vanoli, G.P., 2009a. Carbon dioxide local heat transfer coefficients during flow boiling in a horizontal circular smooth tube. Int. J. Heat and Mass Transfer 52, 4184–4194.

Mastrullo, R., Mauro, A.W., Rosato, A., Vanoli, G.P., Comparison of R744 and R134a heat transfer coefficients during flow boiling in a horizontal circular smooth tube. In: International Conference on Renewable Energies and Power Quality (ICREPQ'09), Valencia, Spain, April 15–17, 2009b.

Moffat, R.J., 1988. Describing uncertainties in experimental results. Experimental Thermal Fluid Sciences 1, 3–17.

Moreno Quibén, J., Thome, J.R., 2007a. Flow pattern based two-phase frictional pressure drop model for horizontal tubes, part I: diabatic and adiabatic experimental study. Int. J. Heat and Fluid Flow 28, 1049–1059.

Moreno Quibén, J., Thome, J.R., 2007b. Flow pattern based two-phase frictional pressure drop model for horizontal tubes, part II: new phenomenological model. Int. J. Heat and Fluid Flow 28, 1060–1072.

Müller-Steinhagen, H., Heck, K., 1986. A simple friction pressure correlation for two-phase flow in pipes. Chemical Engineering Process 20, 297–308.

Nekså, P., Rekstad, H., Zakeri, G., Schiefloe, P., 1998. CO_2 heat pump water heater: characteristics, system design and experimental results. Int. J. Refrigeration 21, 172–179.

Oh, H.-K., Ku, H.-G., Roh, G.-S., Son, C.-H., Park, S.-J., 2008. Flow boiling heat transfer characteristics of carbon dioxide in a horizontal tube. Applied Thermal Engineering 28, 1022–1030.

Panek, J. Evaporation heat transfer and pressure drop in ozone-safe refrigerants and refrigerant-oil mixtures. M.S. thesis, University of Illinois at Urbana-Champaign, 1992.

Papasavva, S., Hill, B., Major, G., 2004. A Comparison of R134a, R134a Enhanced, R744 and R744 Enhanced Automotive Refrigerant Systems Based on Life Cycle. MAC Summit, Washington DC. April 13–15, 2004.

Park, C.Y., Hrnjak, P.S., 2007. CO_2 and R410A flow boiling heat transfer, pressure drop, and flow pattern at low temperatures in a horizontal smooth tube. Int. J. Refrigeration 30, 166–178.

Sawalha, S., 2005. Using CO_2 in supermarket refrigeration. ASHRAE Journal 47, 26–30.

Sawant, N.N., Kim, M.S., Payne, W.V., Domanski, P.A., Hwang, Y. W. A study of in-tube evaporation heat transfer of carbon dioxide. In: 21st IIR International Congress of Refrigeration, Washington DC, USA, 2003.

Schael, A.E., Kind, M., 2005. Flow pattern and heat transfer characteristics during flow boiling of CO_2 in a horizontal micro-fin tube and comparison with smooth tube data. Int. J. Refrigeration 28, 1186–1195.

Shah, M., 1976. A new correlation for heat transfer during boiling flow through pipes. ASHRAE Transactions 82, 66–86.

Steiner, D., Taborek, J., 1992. Flow boiling heat transfer in vertical tubes correlated by an asymptotic model. Heat Transfer Engineering 13, 43–67.

Sun, Z., Groll, E.A. CO_2 flow boiling heat transfer in horizontal tubes, Part I-III. In: Proceedings of 5th IIR-Gustav Lorentzen Conference on Natural Working Fluids, Guangzhou, 2002.

Thome, J.R., Ribatski, G., 2006. State-of-the-art of two-phase flow and flow boiling heat transfer and pressure drop of CO_2 in macro- and micro-channels. Int. J. Refrigeration 28, 1–20.

VDI. VDI-Wärmeatlas (VDI Heat Atlas), Verein Deutscher Ingenieure VDI-Gessellschaft Verfahrenstechnik und Chemieingenieurwessen (GCV), Düsseldorf, 1993.

Wattelet, J.P., Chato, J.C., Christoffersen, B.R., Gaibel, J.A., Ponchner, M., Kenny, P.J., Shimon, R.L., Villaneuva, T.C., Rhines, N.L., Sweeney, K.A., Allen, D.G., Heshberger, T.T., 1994. Heat Transfer Flow Regimes of Refrigerants in a Horizontal Tube Evaporator, ACRC TR-55. University of Illinois at Urbana-Champaign.

Wu, X.M., Zhao, H.Y., Wang, W.C., Jing, L., Zhang, L., 2005. Experimental study on evaporating heat transfer of CO_2 in thin tube. Journal of Engineering Thermophysics 26, 823–825.

Yin, J.M., Pettersen, J., McEnaney, R., Beaver, A., March 1–4, 1999. TEWI Comparison of R744 and R134a Systems for Mobile Air Conditioning. SAE Paper 1999-01-0582. SAE International Congress and Exposition, Detroit, Michigan.

Yoon, S.H., Cho, E.S., Hwang, Y.W., Kim, M.S., Min, K., Kim, Y., 2004. Characteristics of evaporative heat transfer and pressure drop of carbon dioxide and correlation development. Int. J. Refrigeration 27, 111–119.

Yoshida, S., Mori, H., Hong, H., Matsunaga, T., 1994. Prediction of heat transfer coefficient for refrigerants flowing in horizontal evaporator tubes. Transactions the JAR 11, 67–78.

Yu, J., Momoki, S., Koyama, S., 1999. Experimental study of surface effect on flow boiling heat transfer in horizontal smooth tube. Int. J. Heat and Mass Transfer 42, 1909–1918.

Yun, R., Kim, Y., Kim, M.S., Choi, Y., 2003. Boiling heat transfer and dryout phenomenon of CO_2 in a horizontal smooth tube. Int. J. Heat and Mass Transfer 46, 2353–2361.

Zhao, X., Bansal, P.K., 2007. Flow boiling heat transfer characteristics of CO_2 at low temperatures. Int. J. Refrigeration 30, 937–945.