



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1793

NEW CORRELATIONS OF FLOW BOILING HEAT TRANSFER COEFFICIENT BASED ON R1234YF DATA

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Abstract. *R1234yf is a fluid with low GWP and the principal substitute for R134a in automotive applications. Among several studies of this fluid, boiling heat transfer in mini-channels needs special attention due to its importance and scarcity of data. The purpose of this research is to compile pre dry-out R1234yf horizontal flow boiling heat transfer coefficient data available in the open literature, and propose two correlations based on established models. An optimization routine that minimized the sum of squared errors provided the empirical constants for a database comprised of 835 experimental results from five independent sources. Results showed that the new correlations performed better than their counter-parts. A parametric analysis of the correlations on the different sources pointed out that four of the five studies are in good agreement; however, one of them has a different behavior, for unclear reasons.*

Keywords: *R1234yf, boiling heat transfer, mini-channel, two-phase flow*

NOMENCLATURE

Bd	Bond number	u	Mean velocity
Bo	Boiling number	x	Quality
c_p	Constant-pressure specific heat	We	Weber number
D	Diameter	Greek symbols	
F	Enhancement factor for convective parcel	α	Void fraction
Fa	Dimensionless number by Fang	μ	Dynamic viscosity
Fr	Froude number	ρ	Density
g	Gravitational acceleration	σ	Surface tension
G	Mass flux	χ	Lockhart-Martinelli parameter
h	Heat transfer coefficient	Subscripts	
i	Enthalpy	l	Liquid
k	Thermal conductivity	lo	Liquid only
Pr	Prandtl number	m	Mixture
q	Heat flux	nb	Nucleate boiling
Re	Reynolds number	sat	Saturation
S	Suppression factor for nucleate boiling parcel	tp	Two-phase
T	Temperature	v	Vapor

1. INTRODUCTION

In view of the heavy restrictions on greenhouse gas emissions, manufacturers are developing new fluids with low global warming potential (GWP). Sánchez et al. (2017) presented a review of several low-GWP refrigerants depicting their applicability. A particularly interesting fluid is the R1234yf, because its GWP is less than 1, and it has thermodynamic properties close to the R134a, making it a good substitute for use in mobile air conditioning systems. Experimental and numerical studies exist for this application, such as Jarall (2012) and Qi (2015).

Being a new fluid, there are still few experimental results in horizontal flow boiling heat transfer in circular mini-channels for R1234yf. Table 1 describes some of these studies for R1234yf. Saitoh et al. (2011) evaluated the boiling heat transfer and pressure drop of R1234yf and found that nucleate boiling was the dominant mechanism in the low quality region while convective boiling dominated in the high quality one. These findings agreed with those of Lu et al. (2013) and Choi et al. (2014). Del Col et al. (2013) experimented using a heat mechanism that varied the heat flux in the test section and the results pointed out that the heat transfer coefficient (HTC) is highly dependent on the heat flux, whilst changes in mass flow had little impact. Tapia and Ribatski (2017) performed boiling tests using a conventional direct current (DC)-heater for several low-GWP fluids and had similar conclusions for nucleate boiling, though they noted that when convective effects are predominant, the HTC becomes independent of the heat flux and raises with the mass flux. For a detailed revision of R1234yf, Pabon et al. (2016) published a review presenting studies on boiling, condensation and pressure loss, as well as other information like flammability.

As displayed in Table 1, most authors proposed new predictive methods adjusted to their experimental results. The problem in using those methods is the bias acquired for the lack of generality. Less biased correlations are created by fitting data gathered from several independent databases. The aim of this paper is to propose two new correlations, for pre-dry-out horizontal flow boiling of R1234yf in circular mini-channels, adjusted from a database comprised of five independent sources.

Table 1. Horizontal flow boiling R1234yf studies

Authors	T_{sat} (K)	G (kg/m ² .s)	Heat Flux (kW/m ²)	D (mm)	Tube material	Pre dry-out data	Best predictive method
Saitoh et al. (2011)	288.15	100-400	6-24	2.0	Stainless-steel	90	Saitoh et al. (2007)
Del Col et al. (2013)	304.15	200-600	10-100	0.96	Cooper	142	No one
Lu et al. (2013)	283.15	100-500	6-19	3.9	Cooper	37	None tested
Choi et al. (2014)	278.15-284.15	300-500	10-25	1.5-3.0	Stainless-steel	133	Choi et al. (2014)
Tapia and Ribatski (2017)	304.15-314.15	100-400	15-55	1.1	Stainless-steel	433	Tapia and Ribatski (2017)

2. DATABASE

A database of 835 data points of R1234yf two-phase flow boiling heat transfer was compiled from the five papers presented in Tab. 1. The software Webplotdata® converted the data from chart to table. Figure 1 portrays the laminar/turbulent (v/t) flow data distribution. Flow transition at Reynolds number of 2300.

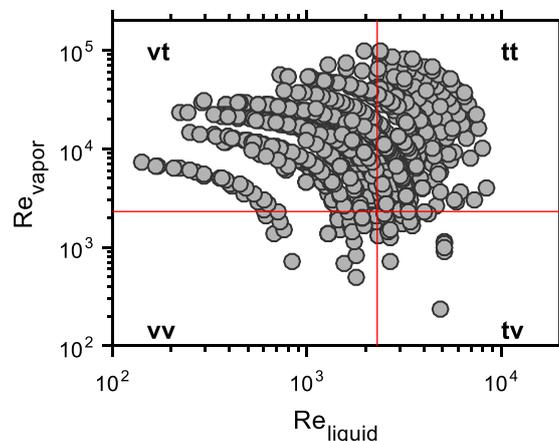


Figure 1. Laminar/turbulent flow data distribution

The correlations proposed are for a set condition of diameter, mass flux and heat flux and flow regimen. Care should be taken if applied under different conditions. Table 2 displays the minimum and maximum values of all parameters used in the optimizations. All units are in SI.

Table 2. Validity range of the proposed correlations

Bd	[1.696 20.62]	i_{iv}	[1.306E+05 1.600E+05]	We_{uv}	[1.449E+01 5.085E+03]
Bo	[1.502E-04 1.434E-03]	k_j	[5.858E-02 6.985E-02]	α	[1.578E-02 8.284E-01]
$c_{p,l}$	[1.308E+03 1.484E+03]	Pr_l	[2.983 3.479]	μ_l	[1.178E-04 1.858E-04]
D	[9.600E-04 3.900E-03]	q	[5.730E+03 1.008E+05]	$u_{l,w}$	[1.122E-04 1.804E-04]
Fa	[1.185E-02 5.234E-01]	Re_l	[1.408E+02 8.416E+03]	u_v	[1.158E-05 1.347E-05]
Fr_m	[4.222E-01 3.638E+01]	Re_{lo}	[8.034E+02 8.932E+03]	ρ_l	[1.027E+03 1.160E+03]
g	9.807	Re_v	[2.332E+02 9.779E+04]	ρ_v	[2.074E+01 6.051E+01]
G	[9.790E+01 6.000E+02]	T_{sat}	[2.781E+02 3.149E+02]	σ	[4.213E-03 8.774E-03]
h_{exp}	[2.508E+03 2.202E+04]	x	[3.000E-03 9.100E-01]	χ	[3.224E-02 1.554E+01]

3. METHODOLOGY

Two well-known correlations from the literature are used as our building block models, being this mainly a task of estimating a non-linear regression. From the Statistical Decision Theory point of view a *squared error loss* function is used, which lead us to a non-linear least squares problem. One of the novel features of our implementation is the usage of the literature-estimated parameters as inputs (initial values) in the optimization routine. We employed the *nlsmin* function, of the stats library in R, to the minimization of the sum of the squared residuals (SSR) and the CoolProp® for the thermodynamic properties.

A secondary, still relevant, issue addressed here is the generalization performance of the estimated correlations, carried out through a cross-validation framework. Leaving technicalities aside, we have a dual goal, where not only to measure the correlations ability to generalize but also to choose one among them. With regards to the generalization performance what we wish is to obtain an estimate of the prediction capability of the models (correlations) on independent test data, that is, we would like to know its test error but what we end up estimating is its expected test error (expected prediction error). At the same time, given two models and a loss criterion, the one with the smallest expected loss (risk) is selected.

With enough data we could randomly divide the dataset into three subsets, one for training (parameters estimation), one for validation (estimate the prediction error and select the best model) and the other for testing the model (assess the test error). However, this is not the case, as this is a complex phenomena with limited data at disposal. As such, we employed cross-validation for estimating the prediction (test) error.

3.1 Error metrics

For ease of comparison, the following error metrics were used to access the correlations performance.

Table 3. Error metrics

Mean Absolute Error (MAE)	$MAE = 1/n \cdot \sum_{i=1}^n h_{pred,i} - h_{exp,i} $
Root Mean Squared Error (RMSE)	$RMSE = \sqrt{1/n \cdot \sum_{i=1}^n (h_{pred,i} - h_{exp,i})^2}$
Mean Relative Error (MRE)	$MRE = 1/n \cdot \sum_{i=1}^n (h_{pred,i} - h_{exp,i})/h_{exp,i}$
Mean Absolute Deviation (MAD)	$MAD = 1/n \cdot \sum_{i=1}^n (h_{pred,i} - h_{exp,i})/h_{exp,i} $
Mean Relative Deviation (MRD)	$MRD = 1/n \cdot \sum_{i=1}^n (h_{pred,i} - h_{exp,i})/h_{exp,i}$

Furthermore, we also report the coverage rate of each correlation, which can be defined as the percentage of predicted values that are contained in a symmetric interval around the observed values given its bandwidth.

3.2 Cross-Validation

Let h_{tp} be the observed value of one of the proposed correlations, \hat{h}_{tp} its estimated value and $\mathcal{L}[h_{tp}, \hat{h}_{tp}]$ the loss function that penalizes the prediction errors. Moreover, suppose that we have a full dataset with $i = 1, \dots, N$ observations and K approximately equal-sized partitions and k is an indexing function indicating whether the observation i is allocated

to K-th partitioning or not (Hastie et al., 2009). Denote by $\hat{h}_{tp}^{-k(i)}$ the estimated value of h_{tp} resulting of the process of fitting the data to the dataset without the K-th part. Then, the cross-validation estimate of the prediction error is given by:

$$CV(\hat{h}_{tp}) = \frac{1}{N} \sum_{i=1}^N \mathcal{L}[h_{tp}, \hat{h}_{tp}^{-k(i)}] \quad (1)$$

This is the K-fold Cross-Validation and some usual choices for K are N, 5 and 10, where the first leads to the Leave One Out Cross-Validation (LOOCV).

In this paper we estimate the full model (K=0), LOOCV, 10-fold CV and an adaption of the Hold-Out method. The latter, henceforth denoted by 70/30, consists of fitting the model on 70% of data and computing the test error with the remaining 30%. As this partitioning is chosen at random, we repeated this process a hundred times and reported the average results in order to have a better understanding of the estimates variability.

3.3 First Correlation

The first correlation is based on the one developed by Tapia and Ribatski (2017), whom adjusted 3409 experimental boiling heat transfer results of R134a, R1234ze(E), R1234yf and R600a. Equations (2-6) show the correlation. The authors preferred a Chen (1966) based correlation, with the enhancement factor for convection (F) and the suppression factor for nucleate boiling (S) calculated as proposed by Kanizawa et al. (2016). They also adopted an asymptotic exponent equal to 2, as proposed by Liu and Winterton (1991), as it better adjusted the nucleate boiling effects to convective effects transition. The HTC related to convective effects is appraised using Dittus and Boelter correlation, while the nucleate boiling effects are estimated using Stephan and Abdelsalam (1980) correlation. The empirical constants were determined using a least square fitting method. Table 4 shows the original values for the empirical constants outlined in session.

$$h_{tp} = [(F \cdot h_l)^2 + (S \cdot h_{nb})^2]^{0.5} \quad (2)$$

$$F = 1 + c_{f,1} \chi^{c_{f,2}} / (1 + We_{uv}^{c_{f,3}}) \quad (3)$$

$$S = c_{s,1} Bd^{c_{s,2}} / [1 + c_{s,3} (10^{-4} \cdot Re_{10} \cdot F^{1.25})^{c_{s,4}}] \quad (4)$$

$$h_l = 0.023 \cdot Re_1^{0.8} \cdot Pr_1^{1/3} \cdot k_l / D \quad (5)$$

$$h_{nb} = 207 \cdot k_l / D \cdot [(q \cdot D) / (k_l \cdot T_{sat})]^{0.745} \cdot (\rho_v / \rho_l)^{0.581} \cdot (\mu_l \cdot c_{p,l} / k_l)^{0.533} \quad (6)$$

Table 4. Empirical constants for Tapia and Ribatski (2017) correlation

	$c_{f,1}$	$c_{f,2}$	$c_{f,3}$	$c_{s,1}$	$c_{s,2}$	$c_{s,3}$	$c_{s,4}$
Original	2.55	1.04	0.194	1.427	0.032	0.1086	0.981

3.4 Second Correlation

The second correlation is based on the one developed by Fang (2013), who adjusted a database of 2286 R134a experimental results from several sources. Equations (7-9) present the correlation. The author used a statistical approach, trying many forms, and adding and removing dimensionless groups as needed. He opted for a least square optimization routine. Table 5 presents the values of the empirical constants for this correlation.

$$h_{tp} = c_1 \cdot (c_2 \cdot S + c_3 \cdot F)^{c_4} \cdot Re_1^{c_5} \cdot Pr_1^{c_6} \cdot Fa^{c_7} \cdot [\ln(1.023 \cdot \mu_l / \mu_{l,w})]^{c_8} \cdot k_l / D \quad (7)$$

$$S = \begin{cases} 30000 \cdot Bo^{1.13} & Bo < 0.0026 \\ 36 & Bo \geq 0.0026 \end{cases} \quad (8)$$

$$F = [x / (1 - x)]^{0.95} \cdot (\rho_l / \rho_v)^{0.4} \quad (9)$$

Table 5. Empirical constants for Fang (2013) correlation

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
Original	0.00061	1	1	1	1	0.4	0.11	-1

Table 6 defines the dimensionless number used in both correlations. Note that to calculate the Weber number relative to vapor velocity, authors of the first correlation used the Kanizawa and Ribatski (2016) void fraction correlation. In addition, they opted for the Da Riva (2012) correlation to estimate Lockhart-Martinelli parameter. In the second correlation, μ_l and $\mu_{l,w}$ are the liquid dynamic viscosity evaluated at the fluid and inner wall temperatures, respectively.

Table 6. Dimensionless parameters used in the correlations

$Bd = (\rho_l - \rho_v) \cdot D^2 \cdot g / \sigma$	$Bo = q / (G \cdot i_{lv})$	$Fa = (\rho_l - \rho_v) \cdot \sigma / (G^2 \cdot D)$
$Fr_m = G^2 / [(\rho_l - \rho_v)^2 \cdot g \cdot D]$	$Pr_l = \mu_l \cdot c_{p,l} / k_l$	$Re_l = G \cdot (1 - x) \cdot D / \mu_l$
$Re_{l0} = G \cdot D / \mu_l$	$Re_v = G \cdot x \cdot D / \mu_v$	$Re_v = G \cdot x \cdot D / \mu_v$
$u_l = G \cdot (1 - x) / [\rho_l \cdot (1 - \alpha)]$	$u_v = G \cdot x / (\rho_v \cdot \alpha)$	$We_{u_v} = \rho_v \cdot u_v^2 \cdot D / \sigma$
$\alpha = \{1 + 1.021 \cdot Fr_m^{-0.092} \cdot (\mu_l / \mu_v)^{-0.368} \cdot (\rho_v / \rho_l)^{1/3} \cdot [(1 - x) / x]^{2/3}\}^{-1}$		
$\chi \rightarrow \begin{cases} \chi_{tt} = [(1 - x) / x]^{0.9} \cdot (\rho_v / \rho_l)^{0.5} \cdot (\mu_l / \mu_v)^{0.1} & Re_v > 1000 \\ \chi_{tv} = 1 / 18.7 \cdot Re_v^{0.4} \cdot [(1 - x) / x]^{0.9} \cdot (\rho_v / \rho_l)^{0.5} \cdot (\mu_l / \mu_v)^{0.1} & Re_v \leq 1000 \end{cases}$		

4. RESULTS

4.1 Correlation I

Figure 2 highlights the performance of the first correlation using the original and adjusted parameters in a predicted versus experimental HTC diagram, while Tab. 7 shows the error metrics and band coverages for this correlation. The correlation with the optimized constants performed better than the original one, that tended to underestimate the HTC approximately 30%. This happened, despite most of the data being from Tapia and Ribatski (2017), because in their paper they adjusted the experimental constants to a database comprised of several different fluids, with thermodynamic behavior quite different from R1234yf. This reveals that a fluid-specific correlation may be more appropriate depending on the application.

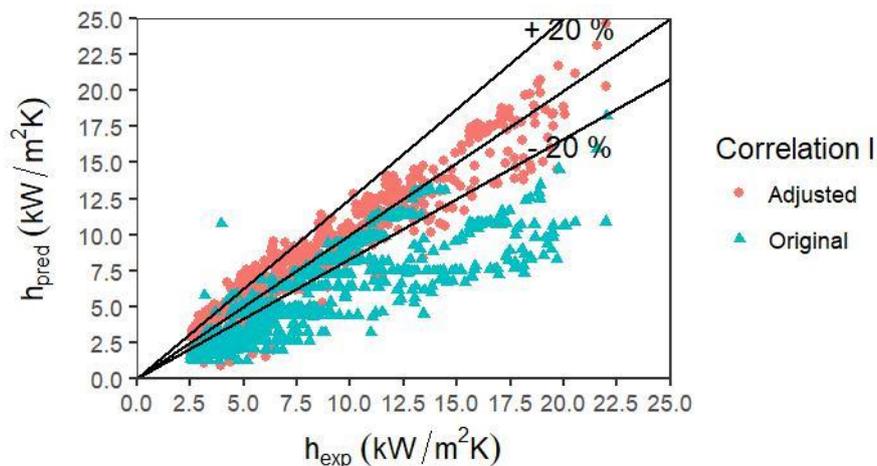


Figure 2. Comparison between the original and adjusted constants for correlation I

Table 7. Errors and coverage for Correlation I

	Error					Coverage					
	MAE	RMSE	MRE	MAD	MRD	5 %	10 %	15 %	20 %	25 %	30 %
Original I	2283	3295	26.20	2.620E-1	-2.496E-1	13.65	30.18	38.68	45.63	50.78	58.32
Proposed I	963.5	1280	13.35	1.335E-1	-3.563E-3	24.91	54.13	69.10	79.88	85.87	90.06

Figure 3 outlines the predicted HTC discriminated by the different databases used. As noted, all data agreed quite well, except the ones from Lu et al. (2013) and Choi et al. (2014). Both authors experimented with low heat flux, as also did Saitoh et al. (2011). This suggests that the addition of the boiling number in the suppression factor for nucleate boiling might improve the results.

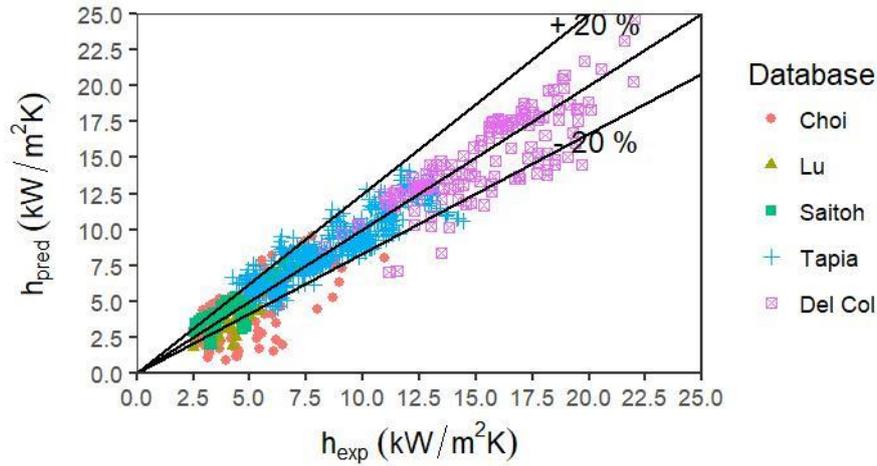


Figure 3. Correlation I by databases

Table 8 displays the constants and Tab. 9 the different errors for the first proposed correlation, including the results of the cross-validation. It is important to highlight that with the exception of the full model, all parameter estimates are mean values, as explained in the methodology section.

Table 8. Empirical constants for Correlation I

	Full base	70/30 Hold-Out	Ten-fold	Leave-one-out
$c_{f,1}$	2.715	3.961	3.572	3.889
$c_{f,2}$	-8.377E-1	-6.508E-1	-6.534E-1	-8.215E-1
$c_{f,3}$	-1.626	-903.1	-36.85	-503.2
$c_{s,1}$	1.431	606.8	30.09	480.2
$c_{s,2}$	-1.310	-1.189	-1.222	-1.286
$c_{s,3}$	-7.216E-1	119.0	4.829	90.82
$c_{s,4}$	-8.367E-2	4.242E-1	3.297E-1	3.035E-1

Table 9. Errors for Correlation I

	Full base	70/30 Hold-Out	Ten-fold	Leave-one-out
MAE	963.5	1088	1095	1016
RMSE	1280	1439	1416	1016
MRE	13.35	14.89	14.92	13.71
MAD	1.335E-1	1.489E-1	1.492E-1	1.371E-1
MRD	-3.563E-3	-1.596E-2	-9.601E-3	-1.156E-3

The outcome of the cross-validation shows that the errors of the correlation obtained using the entire database might be optimistic. That happens because the optimization routine minimizes the sum of squared errors which some error metrics are implicit build on (RMSE for instance). However, the errors obtained through cross-validation are still close enough to the ones using the entire database, which corroborates our claim that they can be used in a more general framework. To put it differently, the empirical evidence supports the thesis of no overfitting.

4.2 Correlation II

Figure 4 portrays the performance of the first correlation using the adjusted parameters against the originals ones, while Tab. 10 presents the error metrics and band coverages for this correlation. Remarkably, the correlation using the original parameters fared really well, only with a slight dispersion along the experimental data. This might have occurred because this correlation was developed only to R134a, which has a thermodynamic behaviour quite similar to the R1234yf. The proposed parameters reduced this dispersion, resulting in a extremely accurate correlation, that predicted 95.9 % of the data under a $\pm 20\%$ bandwidth.

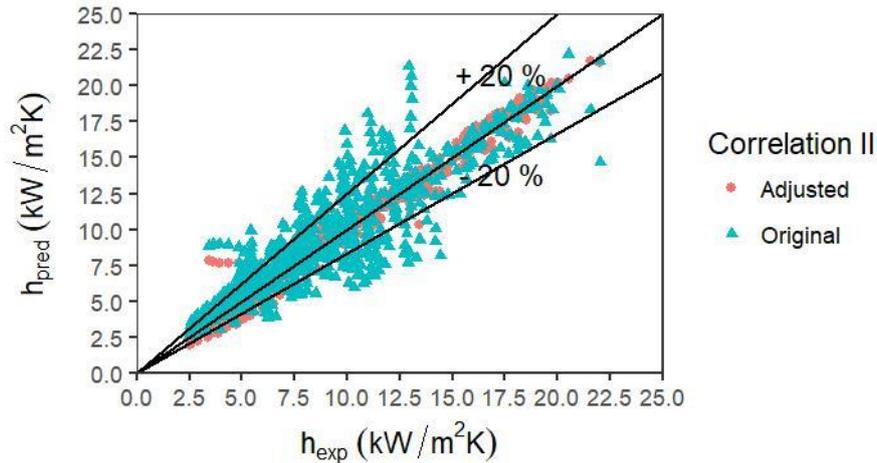


Figure 4. Comparison between the original and adjusted constants for Correlation II

Table 10. Errors and coverage for Correlation II

	Error					Coverage					
	MAE	RMSE	MRE	MAD	MRD	5 %	10 %	15 %	20 %	25 %	30 %
Original II	1337	1878	17.26	1.726E-1	8.541E-2	21.92	40.36	54.01	65.03	76.41	82.87
Proposed II	437.3	634.6	6.184	6.184E-2	-6.538E-3	60.12	81.44	93.05	95.09	98.32	99.28

Figure 5 exhibits the predicted HTC discriminated by the different databases used. The correlation performed well for the entire range, except for some of Lu et al. (2012) data. Differently from the previous correlation, the data obtained under low heat flux was more accurately predicted, perhaps because the boiling number is taken into account in this correlation.

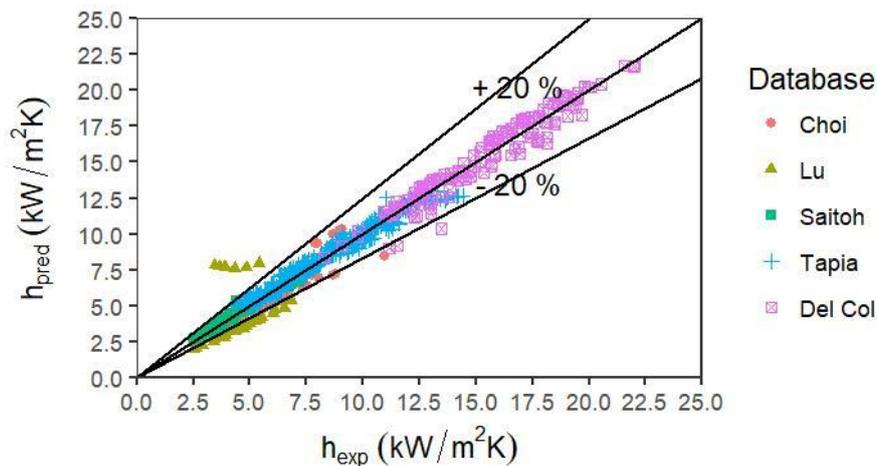


Figure 5. Correlation II by databases

Table 11 shows the constants and Tab. 12 the different errors for the second correlation, including the outcome of the cross-validation. As was the case for first correlation, the estimated parameters exposed in the table are mean values, as the cross-validation routines were repeated a hundred times.

The second correlation, as opposed to the first one, exhibited a smaller deviation between the cross-validation and full base results. I. This suggests that the second correlation is less biased, implying that the model adopted may be better suited for the phenomenon investigated.

Table 11. Empirical constants for Correlation II

	Full base	70/30 Hold-Out	Ten-fold	Leave-one-out
c_1	7.662E-4	9.073E-4	1.000E-3	9.532E-4
c_2	1.044	1.418	1.326	1.329
c_3	7.008E-2	1.105E-1	1.081E-1	1.007E-1
c_4	7.682E-1	7.633E-1	7.560E-1	7.6085E-1
c_5	6.651E-2	8.045E-1	7.760E-2	7.750E-1
c_6	4.940	4.617	4.657	4.676
c_7	-4.237E-1	-4.154E-1	-4.161E-1	-4.163E-1
c_8	-1.208	-1.189	-1.162	-1.176

Table 12. Errors for Correlation II

	Full base	70/30 Hold-Out	Ten-fold	Leave-one-out
MAE	437.3	471.8	462.9	465.4
RMSE	634.6	667.5	655.0	465.4
MRE	6.184	6.732	6.562	6.608
MAD	6.184E-2	6.730E-2	6.560E-2	6.608E-2
MRD	-6.538E-3	-8.286E-3	-5.400E-3	-6.473E-3

4.3 Model selection

Table 13 indicates the best model being the error metric the model selection criteria. The second proposed correlation has the smaller values in the majority of case, with the exception of MRD in the 70/30 hold-out and ten-fold cross-validations. As such, Correlation II with the adjusted constants is suggested over the Correlation I.

Table 13. Model selection

	Full base	70/30 Hold-Out	Ten-fold	Leave-one-out
MAE	II	II	II	II
RMSE	II	II	II	II
MRE	II	II	II	II
MAD	II	II	II	II
MRD	II	I	I	II

5. CONCLUSIONS

This study provides a review of R1234yf flow boiling and proposes two new predictive methods for the pre dry-out heat transfer coefficient of this fluid in small tubes. Those new correlations were obtained adjusting constants to the experimental data, which was gathered from five independent sources. The first correlation proposed consists in an optimization of the Tapia and Ribatski (2017) correlation, while the second is based on Fang (2013) correlation for R134a. In addition, extensive statistical analysis was performed to access the estimates generalization property. The main findings are:

- The new correlations performed better than their counter-parts; however, no care was taken at defining the beginning of dry-out.
- Tapia and Ribatski (2017) correlation underestimate the HTC approximately 30 %. Considering that most of the data was from their study, we expected this correlation to have a better performance. This might be because their correlation was nurtured using data of several low-GWP fluids. In view of that, a fluid-specific correlation might be more suited for design problems.
- Fang (2013) correlation performed quite well, with the predicted values evenly distributed along the experimental value. This probably happened because the correlations is R134a-specific, which is a refrigerant thermodynamically similar to R1234yf.
- Correlation I did not accurately predict the data from experiments with low heat flux, while Correlation II did. The addition of the boiling number in the suppressing factor for nucleate boiling in the first correlation could improve its performance.

- Results of the cross-validation implies that both correlations have a strong generalization capability. In addition, Correlation II had better cross-validation outputs, which means it is more appropriate to the phenomenon at hand.
- Correlation II outperforms Correlation I for the majority of error metrics.
- The correlations proposed could not predict accurately Lu et al. (2013) data for unknown reasons.

6. ACKNOWLEDGEMENTS

CAPES, CEFET-MG, CNPq and FAPEMIG for financial support.

7. REFERENCES

- Chen, J.C., 1966. "Correlation for boiling heat transfer to saturated fluids in convective flow". *Industrial & Engineering Chemistry Process Design and Development*, Vol. 5, p. 322-329.
- Choi, K.-I., Oh, J.-T., Saito, K. and Jeong, J.S., 2014. "Comparison of heat transfer coefficient during evaporation of natural refrigerants and R-1234yf in horizontal small tube". *International Journal of Refrigeration*, Vol. 41, p. 210-218.
- Da Riva, E., Del Col, S.V., Garimella, S.V. and Cavallini, A., 2012. "The importance of turbulence during condensation in a horizontal circular minichannel". *International Journal of Heat and Mass Transfer*, Vol. 55, p. 3470-3481.
- Del Col, D., Bortolin, S., Torresin, D. and Cavallini, A., 2013. "Flow boiling of R1234yf in a 1 mm diameter channel". *International Journal of Refrigeration*, Vol. 36, p. 353-362.
- Fang, X., 2013. "A new correlation of flow boiling heat transfer coefficients based on R134a data". *International Journal of Heat and Mass Transfer*, Vol. 66, p. 279-283.
- Gungor, K.E. and Winterton, R.H.S., 1987. "Simplified general correlation for saturated flow boiling and comparisons of correlation with data". *Chemical Engineering Research and Design*, Vol. 65, p. 148-156.
- Hastie, T., Tibshirani, R. and Friedman, J., 2009. *The Elements of Statistical Learning*. Springer Verlag, New York, 2nd edition.
- Jarall, S., 2012. "Study of refrigeration system with HFO-1234yf as a working fluid". *International Journal of Refrigeration*, Vol. 35, p. 1668-1677.
- Kanizawa, F.T. and Ribatski, G., 2016. "Void fraction predictive method based on the minimum kinetic energy". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 38, p. 209-225.
- Kanizawa, F.T., Tibiriçá, C.B. and Ribatski, G., 2016. "Heat transfer during convective boiling inside microchannels". *International Journal of Heat and Mass Transfer*, Vol. 93, p. 566-583.
- Liu, Z. and 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". *International Journal of Heat and Mass Transfer*, Vol. 34, p. 2759-2766.
- Lu, M.-C., Tong, J.-R. and Wang, C.-C., 2013. "Investigation of two-phase convective boiling of HFO-1234yf in a 3.9 mm diameter tube". *International Journal of Heat Mass and Transfer*, Vol. 65, p. 545-551.
- Mortada, S., Zoughaib, A., Arzano-Daurelle, C. and Clodic, D., 2012. "Boiling heat transfer and pressure drop of R-134a and R-1234yf in minichannels for low mass fluxes". *International Journal of Refrigeration*, Vol. 35, p. 962-973.
- Pabon, J.J.G., Pereira, L.O.C., Porto, M.P. and Machado, L., 2016. "Refrigerante com baixo GWP para sistemas de condicionamento de ar automotivo: R1234yf, Revisão de literatura". In *Congresso Nacional De Engenharia Mecânica. CONEM. Fortaleza, CE, Brazil*.
- Qi, Z., 2015. "Performance improvement potentials of R1234yf mobile air conditioning system". *International Journal of Refrigeration*, Vol. 58, p. 35-40.
- Saitoh, S., Daiguji, H. and Hihara, E., 2007. "Correlation for boiling heat transfer of R-134a in horizontal tubes including effect of tube diameter". *International Journal of Heat and Mass Transfer*, Vol. 50, p. 5215-5225.
- Saitoh, S., Dang, C., Nakamura, Y. and Hihara, E., 2011. "Boiling heat transfer of HFO-1234yf flowing in a smooth small-diameter horizontal tube". *International Journal of Refrigeration*, Vol. 34, p. 1846-1853.
- Sánchez, D., Cabello, R., Llopis, R., Arauzo, I., Catalán-Gil, J. and Torrella, E., 2017. "Energy performance evaluation of R1234yf, R1234ze(E), R600a, R290 and R152a as low-GWP R134a Alternatives". *International Journal of Refrigeration*, Vol. 74, p. 267-280.
- Stephan, K. and Abdelsalam, M., 1980. "Heat-transfer correlations for natural convection boiling". *International Journal of Heat and Mass Transfer*, Vol. 23, p. 73-87.
- Tapia, D.F.S. and Ribatski, G., 2017. "Flow boiling heat transfer of R134a and low GWP refrigerants in a horizontal micro-scale channel". *International Journal of Heat and Mass Transfer*, Vol. 108, p. 2417-2432.

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