Escola de Primavera de Transição e Turbulência
Blumenau 2022

13th Spring School on Transition and Turbulence
September 19th-23rd, 2022, Blumenau, SC, Brazil

EPTT-2022-0006
EXPERIMENTAL METHOD FOR ANALYSIS OF PRESSURE DROP IN PLATE-FINNED HEAT EXCHANGERS WITH DIFFERENT FIN GEOMETRIES

Bruno Carneiro Gutierrez
bruno02gutierrez@gmail.com
Willian Kévin Rauber
williankevinrauber@hotmail.com
Miguel Vaz Júnior
miguel.vaz@udesc.br
Marcus Vinícius Canhoto Alves
marcus.alves@udesc.br
Paulo Sergio Berving Zdanski
paulo.zdanski@udesc.br

Mechanical Engineering Department, Santa Catarina State University, Paulo Malshitzki street, 200, Joinville – SC – Brazil

Abstract. *The present work describes a new experimental methodology to evaluate the pressure drop in finned tube heat exchangers. The method splits the total pressure drop caused by the tube matrix and corresponding holding structure, from which the latter is subtracted from the total pressure drop. A plate-finned heat exchanger with and without upstream vortex generators were tested in wind tunnel. Three fin geometries were assessed: smooth fins and fins with diamond perforations with two different widths. For the case of smooth fins, it was tested vortex generators upstream the tube matrix. The experimental data of pressure drop were compared with numerical results for all fins and for the smooth fins a correlation available in the literature was also used. The results demonstrate that the differences in the angular coefficient in the Pressure Drop by Reynolds Number curves for the numerical and experimental data are very small for the studied Reynolds numbers. The average deviation between numerical and experimental points was approximately 18%, which is an indication of the appropriateness of the proposed experimental methodology and numerical approach used in the simulations.*

Keywords: *Finned tube heat exchangers, pressure drop, wind tunnel, experimental methodology.*

1. INTRODUCTION

The finned tube heat exchangers are extensively used in industrial, household and commercial applications owing to their high efficiency, compact surface area and relatively low cost. In recent years, sustainability issues have led to the development of techniques to enhance the thermal-hydraulic performance of heat exchangers. (Batista, Trp and Lenic, 2022; Rauber et al., 2022). In this context, it is necessary to develop new evaluation methods to improve the prediction of the thermos-hydraulic characteristics. When designing finned tube heat exchangers, knowledge of pressure drop is as important as the heat exchanger coefficient. The amount of useful measured values for pressure drop in finned tubes is, however, much lower than the amount of useful heat exchange coefficient values, resulting in poor reliability equations (Frass, 2015). In current engineering problems, the greatest interest in heat exchanger design is the assessment of the total heat transfer rate related to the Nusselt number and the pressure drop, maximizing the heat exchange and minimizing the pressure drop whenever possible (Bender et al., 2018).

Within this framework, the recent literature presents several numerical and experimental works evaluating heat exchange devices. In the experimental context, many works have been developed to investigate heat transfer in finned tube heat exchangers. For instance, the influence of number and arrangement of tubes (Huang, Yuan and Ay, 2009; Choi et al., 2010); fin pitch (Huang, Yuan and Ay, 2009; Choi et al., 2010), thickness, height, and spacing (Choi et al., 2010, Chen et al., 2014); and air velocity or Reynolds number (Huang, Yuan and Ay, 2009; Vintrou et al., 2013; Chen et al., 2014; Du, Qian and Dai, 2016) in the heat transfer rate and pressure drop have been evaluated. The numerical simulation has gained space in research works due to its low cost in relation to the development of experimental prototypes. For instance, numerical works investigate new arrangements of tubes (Bender et al., 2018) and, mainly, new fin design (Singh, Sorensen and Condra, 2017; Boukhadia et al., 2018; Xue et al., 2018; Rauber et al., 2022).

Some works demonstrate that, in addition to fins, thermal efficiency of heat exchangers can be increased by vortex generators (VG). This device causes fluid separation and increases the turbulence, leading the heat transfer rate to increase, in the other hand, growth of the pressure drop effect (Zdanski, Pauli and Dauner, 2015). Experimental and numerical works assessing the influence of parameters, such as VG type (Salviano, Dezan and Yanagihara, 2016; Samadifar and Toghraie, 2018), positioning relative to the tubes (Zanatta et al., 2020), incidence angle of the delta winglet VG and free-stream velocity (Zdanski, Pauli and Dauner, 2015), in the heat transfer coefficient and pressure drop have been developed in recent years.

In this study, a new experimental methodology to evaluate the pressure drop in finned tube heat exchangers is presented. The methodology consists in wind tunnel experiments splitting the total pressure drop caused by (1) the tube matrix, (2) corresponding holding structure and (3) vortex generators in separated parts. Initially, pressure drop in the holding structure (without the other parts) is measured, followed by measurement of the total pressure drop. In order to validate the results, the pressure drop curves obtained with CFD analysis are compared to those obtained using the experimental apparatus (Rauber, 2021) and to a correlation proposed in the literature.

2. EXPERIMENTAL PROCEDURE

The experimental apparatus comprises a suction type wind tunnel with open circuit that has a test section of $250 \times 250\ mm^2$ and aspect ratio of 1:6, as shown in Fig. 1.

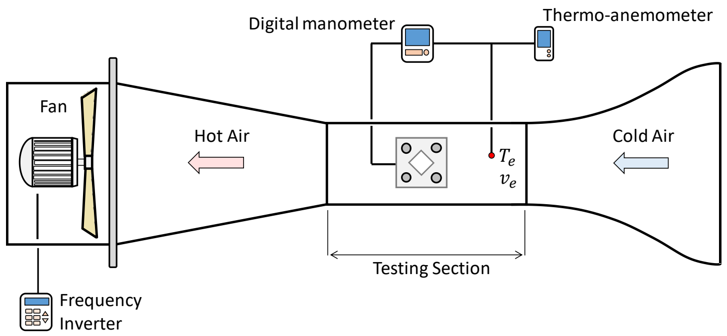

Figure 1. Wind tunnel's schematics.

This wind tunnel has been utilized for several studies involving heat exchange and aerodynamics, such as Bender et al. (2018), González, Vaz Júnior and Zdanski (2019), Zanatta et al. (2020), Rauber (2021) and Rauber et al. (2022). According to Zdanski, Pauli and Dauner (2015), the intensity of the flow turbulence entering the empty test section is less than 1%.

A thermo-anemometer and a digital manometer from the Kimo brand were utilized to measure the data from the experiments. In order to reach the Reynolds numbers of interest, velocities of 5.4, 6.8, 8.4 and 10.1 m/s were utilized with fluid properties measured at the entrance section for a room temperature of 296 K.

2.1 Finned tube heat exchanger assembly

The research developed by González, Vaz Junior and Zdanski (2019) showed through a hybrid methodology that the lower temperature regions in the fin's center have diamond shape, shown in Fig. 2. Rauber (2021) and Rauber et al. (2022) assessed the heat exchange in fins with diamond shape perforations for different dimensions.

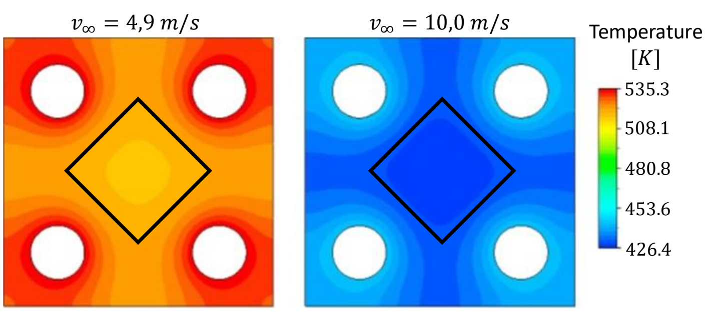

Figure 2. Temperature distribution obtained by González, Vaz Junior and Zdanski (2019).

The apparatus utilized in the experiments were previously built and tested by Rauber (2021) and Rauber et al. (2022), being manufactured with mechanical interference aiming to reduce the contact thermal resistance between heaters. The fins were laser cut, in order to guarantee the desired precision. The holes, in which the heaters are fitted, were pre-machined and the fins were forced until they reached their positions. The final configuration and main parameters are shown in Fig. 3 with dimensions presented in Tab. 1 and isometric view in Fig. 4.

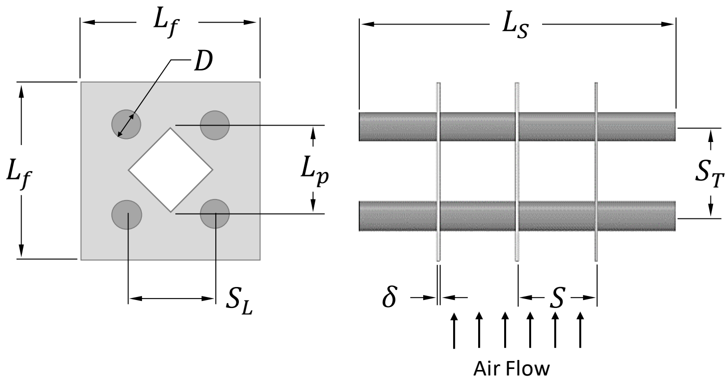

Figure 3. Heat exchanger dimensions and parameters.

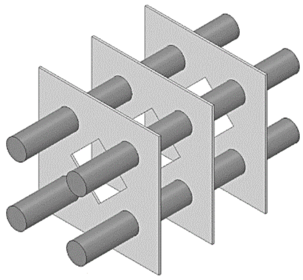

Figure 4. Heat exchanger isometric view.

Table 1. Dimensional parameters for heat exchanger from Rauber et al. (2022) work.

Parameter	Symbol	Value
Fin spacing	S	$42.50\ mm$
Fin length	L_f	$96.00\ mm$
Tube diameter	D	$16.0\ mm$
Tube length	L_s	$170.0\ mm$
Fin thickness	δ	$1.50\ mm$
Longitudinal pitch	S_L	$48.0\ mm$
Transversal pitch	S_T	$48.0\ mm$
Number of fins	N_f	3
Number of tubes	N_s	4

The heat exchangers are supported by a structure, named here as holding structure, inside the test section of the wind tunnel. There is contact only between the ends of the tube and the holding structure, preventing too much surface area being isolated by the structure. The assembly of the holding structure and the finned tube heat exchanger is exemplified in Fig. 5.

Figure 5. Holding structure and finned tube heat exchanger in the test section.

2.2 Vortex generators assembly

Zanatta et al. (2020) evaluated the heat transfer in a finned tube heat exchanger with upstream VGs, which were 3D printed with PLA material. The VGs geometry was based on the best parameters suggested by Zdanski, Pauli and Dauner (2015). The chosen configuration to evaluate the pressure drop was the one that, according to Zanatta et al. (2020), exhibited the most increase in heat exchange (the parameters are shown in Fig. 6 and the corresponding values in Tab. 2). The apparatus fitted in the test section of the wind tunnel in depicted Fig. 7.

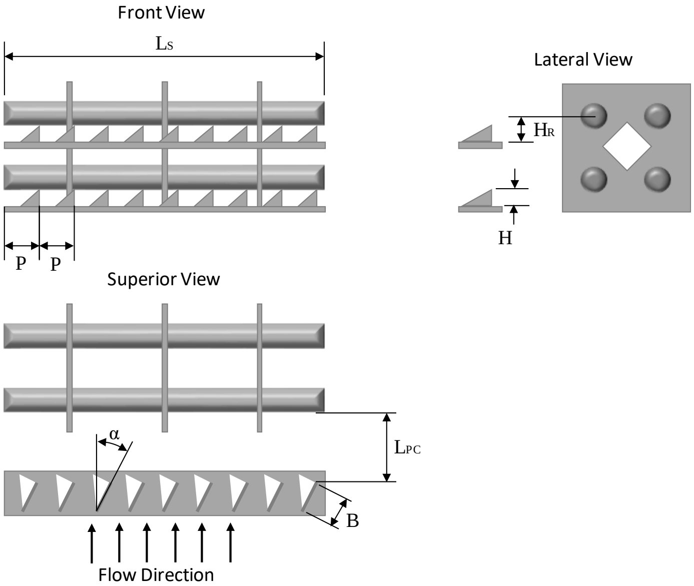

Figure 6. Parameters of the VGs and its assembly in the holding support from Zanatta et al. (2020).

Table 2. Geometric parameters of the vortex generators.

Parameter	Values
P/D	1.75
L_{PC}/D	1.94
$A\ [rad]$	0.72
B/D	1.75
H/D	1.00
S_T/D	3.00
S_L/D	3.00
H_R/D	1.00

Figure 7. Vortex generator and heat exchanger assembly.

2.3 Measure procedure

Firstly, the holding structure was assessed in order to obtain its pressure drop plus the intrinsic pressure drop from the test section (shown in Fig. 8). Then, the experiment was performed for all fin configurations, i.e.: without perforation (the reference fins), 32 mm perforation and 48 mm perforation. Also, the pressure drop was evaluated with addition of vortex generators for the following cases: structure and VG (without heat exchanger) and structure supporting the reference fins heat exchanger and VG. Table 3 presents the assembly of these equipment and the names that will be used in the discussion of results.

Figure 8. Evaluation of the holding structure's pressure drop.

Table 3. Characteristic size L_p for different diamond perforation fins from Rauber et al. (2022).

Configuration	**Assembly name**	**L_p size [mm]**	**Removed Area [mm²]**	**Fraction [%]**
Reference Fin Without VG	A	0	−	Reference
Reference Fin With VG	B	0	−	Reference
Perforated Fin Without VG	C	32.00	511.908	5.55
Perforated Fin Without VG	D	48.00	1152.093	12.50

Figure 8 shows also the instruments used to measure the velocity and temperature at the inlet test section (**1** - hotwire anemometer) and two pressure gauges (**2** and **3** - piezoelectric membrane of the digital manometer). It is known that the pressure drop is associated with nonlinear complex phenomena, and that the interaction among the objects in the test section generates a flow field which is not equivalent to the flow field of each object separately. Nevertheless, the proposed methodology assumes that the pressure drop can be evaluated linearly as a sum, composed by the total pressure drop (Δp_{total}), pressure drop from the holding structure summed to the test section ($\Delta p_{section} + \Delta p_{structure}$) and pressure drop from holding structure mounted with the VGs summed to the test section. Hence, it is possible to isolatedly calculate the pressure drop from the heat exchanger and pressure drop from the VGs, according the equations:

$$\Delta p_{exchanger} = \Delta p_{total} - (\Delta p_{section} + \Delta p_{structure}) \ , \tag{1}$$

$$\Delta p_{VG} = \Delta p_{total} - (\Delta p_{section} + \Delta p_{structure}) \ . \tag{2}$$

It is worth noting that, in the Eq. (2), the total pressure drop (measured) was obtained with only VGs and the holding structure in the test section. The hydraulic diameter is calculated according:

$$Dh = \frac{4V'\Psi}{A'} \quad \text{where} \quad \begin{aligned} V' &= S_T S_L (S-\delta) \\ A' &= 2(S_T S_L - \pi D^2/4) + \pi D (S-\delta) \\ \Psi &= 1 - \delta/S - (\pi D^2/4)\,(S-\delta)/(S_T S_L S) \end{aligned} \ . \tag{3}$$

The Reynolds number for the comparisons is calculated based on:

$$Re_{Dh} = \frac{\rho_a \, u_{max} \, Dh}{\mu_a} \ , \tag{4}$$

where ρ_a and μ_a are the specific mass and dynamic viscosity of air, respectively, and u_{max} is defined by: $u_{max} = {u_\infty}/{\Psi}$. For the comparisons between the experimental data and the literature correlation were made using Kaminski and Gross equation, explained for Frass (2015). The pressure drop correlation is:

$$\Delta p_{exchanger} = C_1 \, Re_{Dh}^{1/3} \left(\frac{Dh}{S_L}\right)^{3/5} n_r \frac{S_L}{Dh} \frac{\rho u_\infty^2}{2\Psi^2} \ , \tag{5}$$

in which n_r is the number of tube lines and $C_1 = 6$ for inline arrangement. In the above equations all measures for the calculations are in the Fig. 3 and Tab. 1.

3. RESULTS AND DISCUSSIONS

In this section, it is presented all data obtained from the wind tunnel measurements and the comparative analysis with data from the literature and from the CFD analysis performed by Rauber (2021). In order to make coherent evaluations, the data from the literature and from numerical source were rounded to magnitude order of 1 Pa (manometer resolution). The measurements results are shown in Tab. 4:

Table 4. Wind tunnel data - pressure drop from the three fins configurations, pressure drop from the holding structure and pressure drop with the addition of VGs.

Velocity (u_∞) $[m/s]$	**Assembly A** $[Pa]$	**Assembly B** $[Pa]$	**Assembly C** $[Pa]$	**Assembly D** $[Pa]$	**Holding structure** $[Pa]$	**Holding structure and VG** $[Pa]$
5.4	11	12	11	9	4	6
6.8	17	20	17	15	7	10
8.4	25	27	25	24	11	15
10.1	34	40	38	41	16	20

The results obtained for the assembly A (reference fins from Tab. 3 without VG) are shown in Fig. 9. It is observed that the slope of the curve obtained by Rauber (2021) and by the present experiments are very close, being the average variation equal to 11%. However, when compared to the literature (Kaminski and Gross correlation from Frass (2015)), both curves present an average variation of approximately 36%.

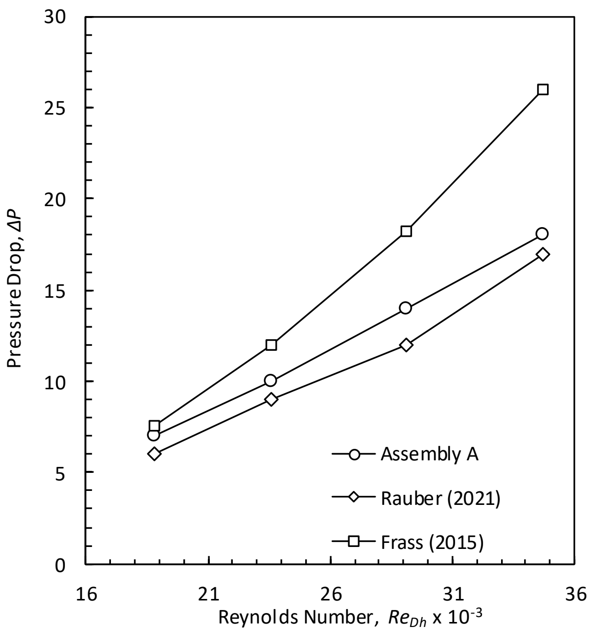

Figure 9. Experimental, numerical and literature correlation comparison for heat exchanger with Assembly A.

The correlation used for the validation of the pressure drop (Frass, 2015) use a specific hydraulic diameter, which was also used in the present work to evaluate the Reynolds number at different velocities, as shown in section 2.3.

For the case of heat exchanger assembly C (Fig. 10(a)), it is noted that the slopes of the curves are similar for low Reynolds numbers and the average variation is approximately 14%. For the case of heat exchanger assembly D (Fig. 10(b)), the results present a similar behavior to the case of smaller perforations, being the slopes also similar for low Reynolds numbers with average variation of approximately 17%.

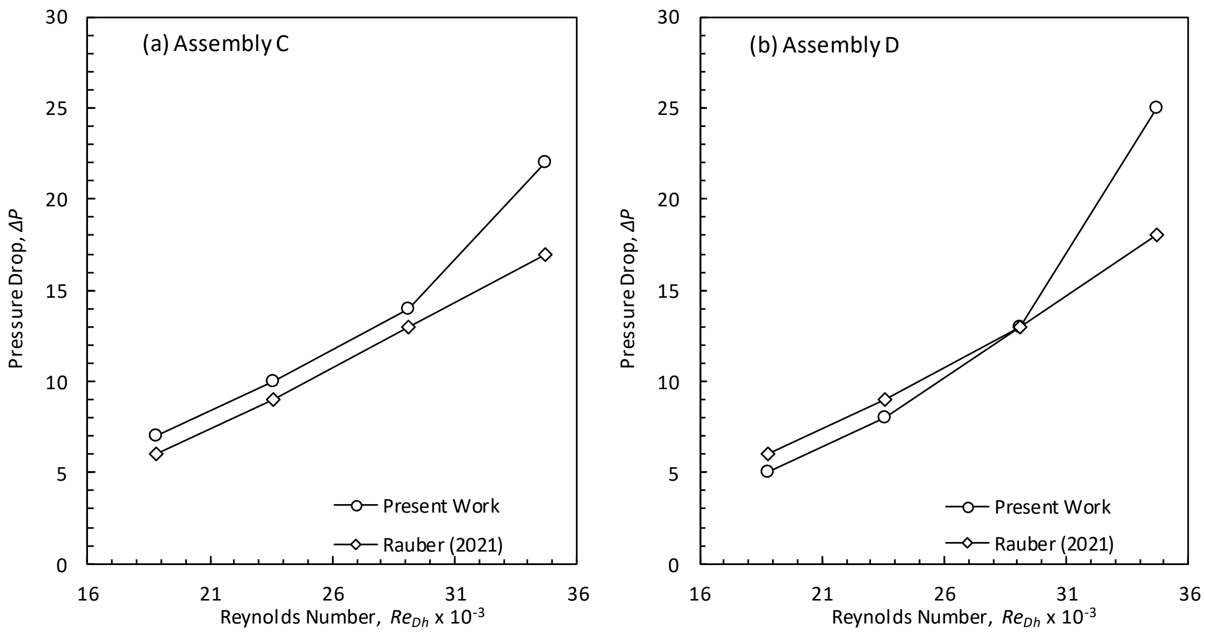

Figure 10. Experimental and numerical comparison for (a) Assembly C and (b) Assembly D.

The pressure drops increase due to VGs was assessed for the reference fins case, assembly B, once it was assumed that the increase would remain the same for the others configurations. The results obtained for this configuration are shown in Fig. 11. It is observed that the VGs not only increased the pressure drop for each Reynolds number, but also increased the curve slope in approximately 30%. The average pressure drop increase due to the VGs was 3 Pa.

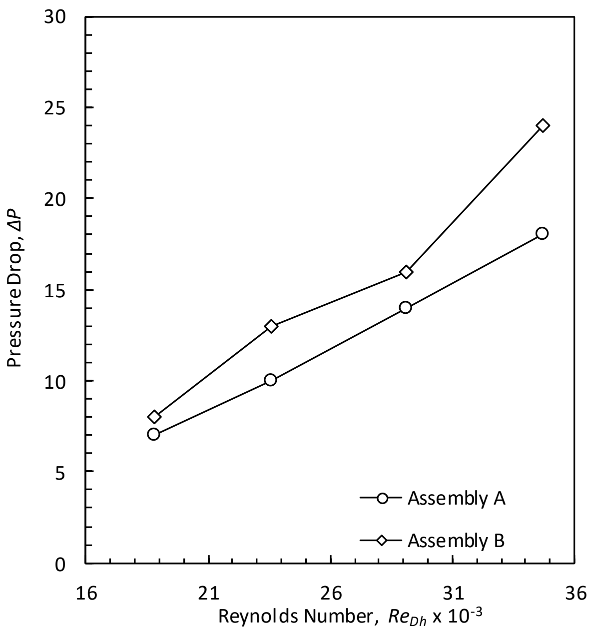

Figure 11. Pressure drops comparison of Assemblies A and B.

Finally, it was evaluated the data for all three configurations of fins. In Fig. 12 it was observed that the slopes of the curves are similar for low Reynolds numbers and diverge at the highest value, being the average variation approximately 21%.

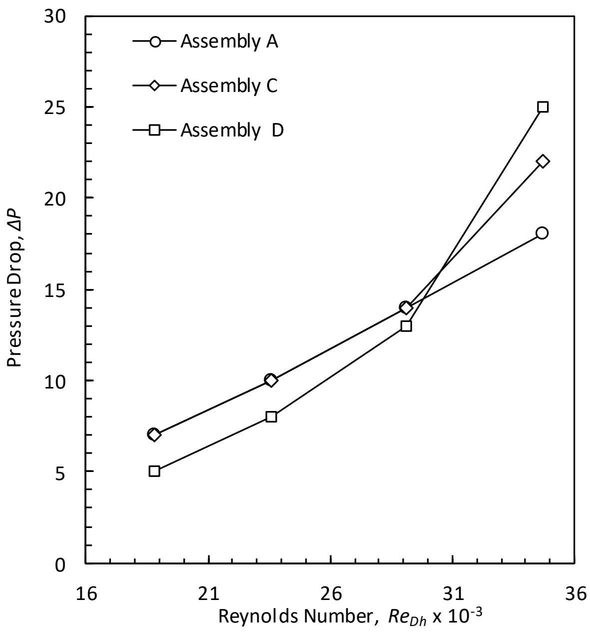

Figure 12. Experimental comparison of the three fins configurations.

The average variation of all experimental data when compared to the numerical and literature correlation data is 18%, which is considered satisfying, once the methodology applied considers a linear simplification of an intrinsic non-linear problem.

Furthermore, it needs to be pointed out that the results obtained for the three lower Reynolds numbers do not have physics representativity, once they are too close from to the manometer resolution. It was not possible to evaluate the pressure drop for higher Reynolds numbers due to the wind tunnel's structural limitations. However, it was possible to capture the non-linearity caused by the introduction of perforation in the fins, the maximum Reynolds number tested indicate that the turbulence increases the vortex effects inducing a higher pressure drop in the system, this was explained by Rauber (2021) that the flow separation on the tube surfaces will collide in the perforation of the fin, causing more perturbation in this region, so the fin with the largest perforation is the one that causes the higher pressure drop at higher Reynolds number.

4. FINAL REMARKS

The present work experimentally evaluated the pressure drop in a finned tube heat exchanger under forced convection, testing a new methodology to calculate separately the loss of one of the components present in the test section of a wind tunnel. The results are valid for fins without notch and with notch of $32\ mm$ and $48\ mm$, within the range of Reynolds number of approximately $18{,}800 < Re_{Dh} < 34{,}700$. The upper limit is due to the structural limitations of the wind tunnel used.

As numerical results were taken as a basis for the experimental validation (it has a certain residual error) and because the uncertainty associated with the manometer measurements, it was already expected that the errors obtained would not be low. However, for the three cases studied without the addition of VGs, the angular coefficient of the experimental and theoretical curves showed no difference for the first three evaluated velocities. Therefore, this fact is a strong indication of the validity of the proposed methodology.

As for the comparison with the literature, through the correlation from Frass (2015), it is noted that it is conservative and overestimates the head loss, with a difference of 36% in the angular coefficient of the curves, with the theoretical curve farther from the numerical curve than from the experimental curve.

For the case with the addition of turbulence promoters, it is noted that their influence is increasing as the Reynolds number increases. Furthermore, the ΔP values found when subtracting the pressure drop of the matrix with promoters from the matrix without promoters had similar values to those found when subtracting the head loss of the support with promoters from the head loss of only the support, which indicates reliability in the methodology, since a similar result was obtained in two different ways.

The three experimental curves showed very similar pressure drops for low Reynolds numbers, as obtained by Rauber (2021). In the present study, however, higher errors were obtained, possibly due to the resolution of the manometer used ($1\ Pa$). Considering that the methodology proposed by the present work is very simplistic, as it is based on a linear operation in an extremely complex and non-linear problem, obtaining the average of all experimental points in relation to the numerical curves and the curve of the literature of approximately 18% is quite satisfactory. Thus, the methodology can be considered valid and can be reproduced in other studies.

5. ACKNOWLEDGEMENTS

The first and second author thanks the “Universidade do Estado de Santa Catarina (UDESC) – Programa de Bolsas de Monitoria de Pós-Graduação (PROMOP)” for the scholarship provided. All authors acknowledge the FAPESC, Finance Code 2021TR843, and the last author thanks the financial support provided by the “Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)” under grant 306821/2021-4.

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