ENCIT2022-0725
THERMAL-HYDRAULIC CHARACTERIZATION OF A TRIANGULAR MICROCHANNEL REGENERATOR VIA THE SINGLE-BLOW METHOD

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Abstract. *Despite their importance in several engineering applications, there are conflicting results in the literature regarding the thermo-hydraulic behaviour of microchannel thermal regenerators, especially concerning the Nusselt number and their relation with equivalent microchannels of the same geometry. In this work, two La-Fe-Si triangular microchannel regenerators were submitted to pressure drop and single-blow tests to determine their Ergun's constant and Nusselt number. The pressure drop tests consisted of measuring the regenerator pressure drop in steady flow for several mass flow rates and finding the Ergun's constant from a best fit of the data. The single-blow tests consisted of submitting the regenerator to a steady-state flow in which the inlet temperature suffers a step wise change and measuring the temperature profile of the outlet of the regenerator. The energy equations for both the solid and fluid in this situation are know and are a function of the NTU, allowing for its value (and consequently, the Nusselt number) to be determined through a curve fitting method. The results showed an Ergun's constant of 0.17, indicating a much smaller pressure drop than in a packed bed of spheres, as expected, and that the Nusselt number does not seem to depend on the Reynolds number and has a value close to 2.49, which is known to be the Nusselt number of a triangular macrochannel with a constant wall temperature.*

Keywords: *microchannel regenerator, triangular microchannel, pressure drop, heat transfer, single blow*

1. INTRODUCTION

Regenerators are storage-type heat exchangers in which the flow channels are alternately occupied by hot and cold fluid flows, resulting in an indirect heat transfer between the streams through solid matrix. They have a wide range of applications, such as building ventilation systems, gas turbine energy recovery units and air-preheating systems in power plants, most of which involve gases (Nellis and Klein, 2009). However, some not-in-kind cooling technologies (i.e., elastocaloric, electrocaloric, magnetocaloric) use liquid solutions as thermal fluids in regenerative cycles (Klinar and Kitanovski, 2020). Therefore, it is crucially important to understand and properly describe the thermal and hydraulic behavior of a flow through the channels in the many configurations that they may assume.

In magnetic refrigeration, packed beds of spheroidal magnetocaloric particles are the most common solid matrix regenerator geometry, but other porous bed types have also been extensively evaluated (Trevizoli *et al.*, 2017; Lei *et al.*, 2017). Recently, new manufacturing techniques enabled the development of novel porous geometries for active magnetic regenerators (AMRs) (Navickaitė *et al.*, 2020), among them blocks made from La-Fe-Si alloys containing parallel triangular microchannels (i.e., with a hydraulic diameter smaller than 1 mm). For this particular AMR geometry, there has been some indication that the thermal-hydraulic behavior in laminar flow differs from the classical macrochannel theory since a dependence of the Nusselt number on the Reynolds number has been found via an indirect assessment of the transport coefficients using a differential AMR model (Liang *et al.*, 2021). Earlier reviews by Morini (2004) and Sharp *et al.* (2006) already revealed and discussed contradicting experimental results for the Poiseuille and Nusselt numbers in fully-developed laminar liquid flows in microchannels. However, the general conclusion from such reviews was that, if carefully controlled, experimental measurements of transport coefficients in microchannels should agree with the classical macrochannel theory. More recently, El-Genk and Pourghasemi (2019) proposed a correlation for the Nusselt number in microchannels as a function of its dimensions, aspect ratio and the inlet Reynolds and Prandtl numbers. In this case, the Nusselt number increased with the Reynolds number. Therefore, despite the vast literature available regarding the topic, a consensus is yet to be reached regarding some of the most fundamental questions concerning microchannels.

With that in mind, the present work is the first to conduct dedicated experiments to determine the single-phase liquid pressure drop and interstitial heat transfer through La-Fe-Si regenerators with parallel triangular microchannels. While the pressure drop is measured and regressed using a steady-state approach, the interstitial heat transfer coefficient is obtained from the single-blow method (Heggs and Burns, 1988; Abuserwal, 2017) and reported in terms of a Nusselt number based on the Reynolds number.

2. NUMERICAL MODEL AND THE SINGLE-BLOW METHOD

To describe the pressure drop, a one-dimensional model utilizing a porous medium approach was developed which considered both the inertial and viscous microscopic effects, resulting in a simplified version of the Brinkman-Forcheimer equation given by (Kaviany, 1995):

$$\frac{\partial p}{\partial x} = -\frac{\mu}{K}u_{\mathrm{D}} - \rho\frac{c_{\mathrm{E}}}{\sqrt{K}}u_{\mathrm{D}}^2 \tag{1}$$

where p is the pressure, x is the position along the regenerator axis, μ is the dynamic viscosity, u_{D} is the Darcy velocity and ρ is the density. c_{E} is a constant in the inertial term sometimes referred to as Ergun's Constant, and determining its value is one of the goals of this work. Lastly, K is the permeability of the porous medium, which is determined using a capillary model that results in:

$$K = \frac{2\varepsilon D_{\mathrm{h}}^2}{4Po} \tag{2}$$

where ε and D_{h} are the matrix's porosity and hydraulic diameter, respectively, and Po is the Poiseuille number.

In order to determine the relationship between the Nusselt and Reynolds numbers, a proper way to experimentally measure the interstitial heat transfer coefficient, h, needed to be established. The single blow technique (Heggs and Burns, 1988; Abuserwal, 2017) was determined to be the most appropriate to achieve this due to both its simplicity and its compatibility with the available experimental apparatuses (see Sec. 3). This method, first developed during the late 1920s (Pucci *et al.*, 1967), consists of measuring the temperature response given by a fluid at the outlet of a thermal regenerator after a known temperature change is applied to the fluid at the inlet. With this result, it is possible to indirectly calculate the Number of Transfer Units (NTU) by solving a system of differential equations and applying a curve fitting technique (Heggs and Burns, 1988). Fig. 1 shows a flowchart summarizing the main steps of this process.

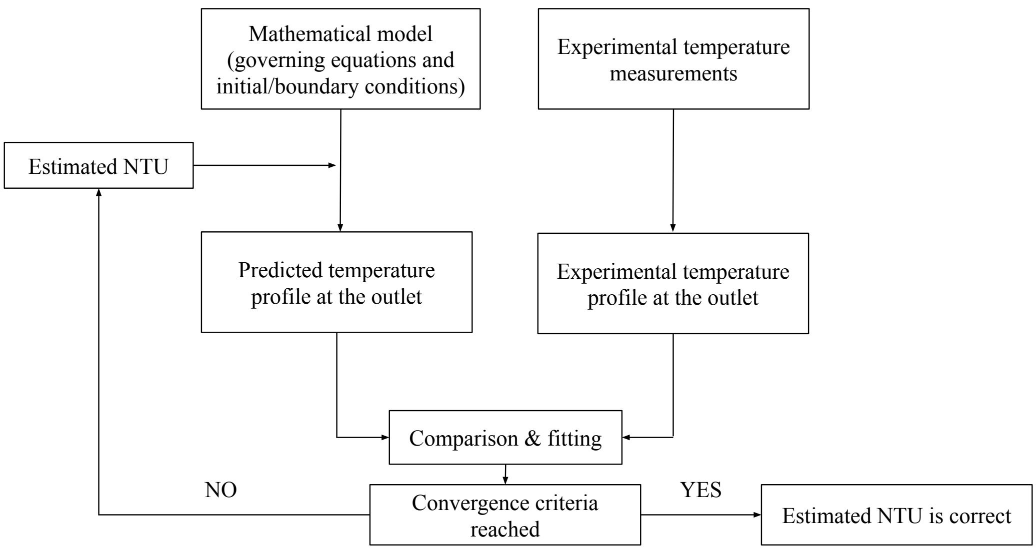


Figure 1. Flowchart illustrating the single blow method algorithm

The numerical model consists of two dimensionless 1-D, time-dependent energy equations for the solid and fluid phases (Luo *et al.*, 2001):

$$\frac{\partial \theta_{\mathrm{s}}}{\partial \tau} - K_{\mathrm{m}}\frac{\partial^2 \theta_{\mathrm{s}}}{\partial X^2} + NTU(\theta_{\mathrm{s}} - \theta_{\mathrm{f}}) = 0 \tag{3}$$

$$\frac{1}{B}\frac{\partial\theta_{\mathrm{f}}}{\partial\tau}+\frac{\partial\theta_{\mathrm{s}}}{\partial X}-\frac{1}{Pe_{\mathrm{x}}}\frac{\partial^2\theta_{\mathrm{f}}}{\partial X^2}+NTU(\theta_{\mathrm{f}}-\theta_{\mathrm{s}})=0 \tag{4}$$

where θ_{s} and θ_{f} represent the matrix and fluid dimensionless temperatures, respectively, τ is the dimensionless time, Pe is the Peclet number, X is the dimensionless axial position and K_{m} and B are dimensionless terms related to the longitudinal diffusion and time adjustment. For heating tests, the initial condition for the temperatures is $\theta_{\mathrm{f}}=\theta_{\mathrm{s}}=0$ while for cooling tests it is $\theta_{\mathrm{f}}=\theta_{\mathrm{s}}=1$. In all cases, the inlet temperature is known during the entire experiment and the matrix is assumed to be thermally insulated, i.e., there is no heat exchange on both the inlet and the outlet. The differential equation system is solved through a finite differece scheme and a totally implicit approach for the time derivatives. Three curve fitting techniques were used to determine the NTU and, ultimately, the relationship between the Nusselt and Reynolds numbers: (i) a direct comparison of the temperatures using the least squares method (T), (ii) a comparison of the temporal derivatives using the least squares method (gT) and (iii) matching the maximum temporal derivative (gM) (Heggs and Burns, 1988). Before the tests with the La-Fe-Si regenerators, the model was validated against literature data (Luo *et al.*, 2001).

3. EXPERIMENTAL WORK

The experimental apparatus presented in Fig. 2 consists of two thermal baths to emulate ideal (hot and cold) heat exchangers, a pump, a hydraulic system with valves to direct the fluid flow from the hot to the cold end and vice-versa, and the regenerator test section. Thermocouples, pressure transducers and mass flow meters are installed on each end.

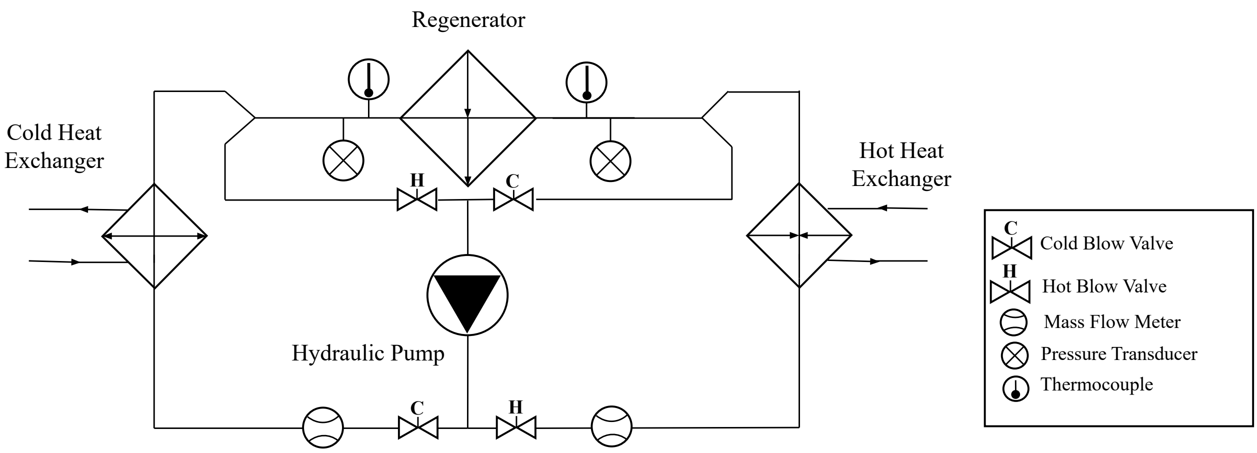


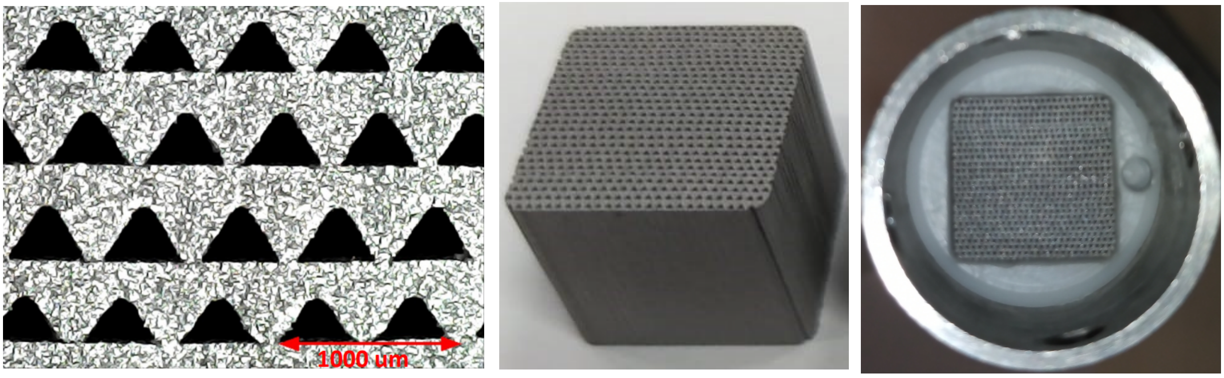
Figure 2. Flowchart illustrating the single blow method algorithm

The pressure drop tests consist of pumping fluid in one direction until steady-state and taking the difference between the absolute pressure measurements on each side. This is repeated for several mass flow rates. For a heating single blow test, the cold bath is set at the initial system temperature, while the hot bath is set at the desired final temperature. Fluid is then released from the cold bath until the initial temperature is reached in the regenerator. Then, the valves are switched and hot fluid starts to flow through the regenerator, triggering the step-like temperature wave in the porous medium. For the cooling tests, the process is reversed.

Two different La-Fe-Si regenerators with triangular microchannels (Fig. 3.a) were tested in this work. Both had a 14-mm x 14-mm cross-section, an estimated channel hydraulic diameter of 0.217 mm and were supplied by Vaccumschmelze GmbH & Co. Both regenerators consisted of 4 blocks (Fig. 3.b) which were encased in an acetal pellet and stacked on top of each other inside a steel casing (Fig. 3.c). A free space of approximately 1 mm was left between each block to avoid any misalignment between the channels. The regenerators differed from one another mainly in length. The first regenerator, LTC050, had a length of 49 mm while the second one, LTD081, had a length of 80 mm. Table 1 summarizes the main characteristics of both regenerators.

Table 1. Characteristics of the LTC050 and LTD081 regenerators.

Regenerator	**LTC050**	**LTD081**
Mass (g)	50	81
Height x Width x Length (mm x mm x mm)	14 x 14 x 49	14 x 14 x 80
Estimated Heat Transfer Area (mm^2)	0.039	0.062
Average Hydraulic Diameter (mm)	0.217	0.217



(a) (b) (c)

Figure 3. (a) Channel cross-section. (b) Regenerator block. (c) Regenerator inside a casing.

4. RESULTS

Regenerators LTC050 and LTD081 were submitted to pressure drop and single blow tests for thermohydraulic characterization. All pressure drop tests were conducted under a set ambient temperature of 25 °C and the results for Regenerator LTC050 were used to determine Ergun's constant value. This was achieved by applying the least-square curve fitting method to the pressure drop results predicted by Eq. 1 and selecting the Ergun constant value that better fitted the data, which was determined to be approximately 0.17. Fig. 4 shows the behaviour of the fitting technique parameter R^2 for different values of c_E, with the optimal result clearly falling near 0.17.

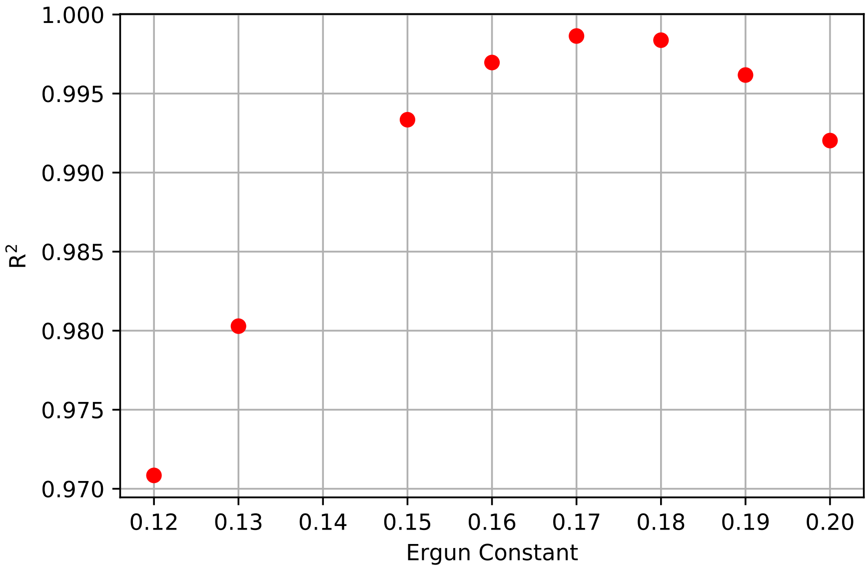
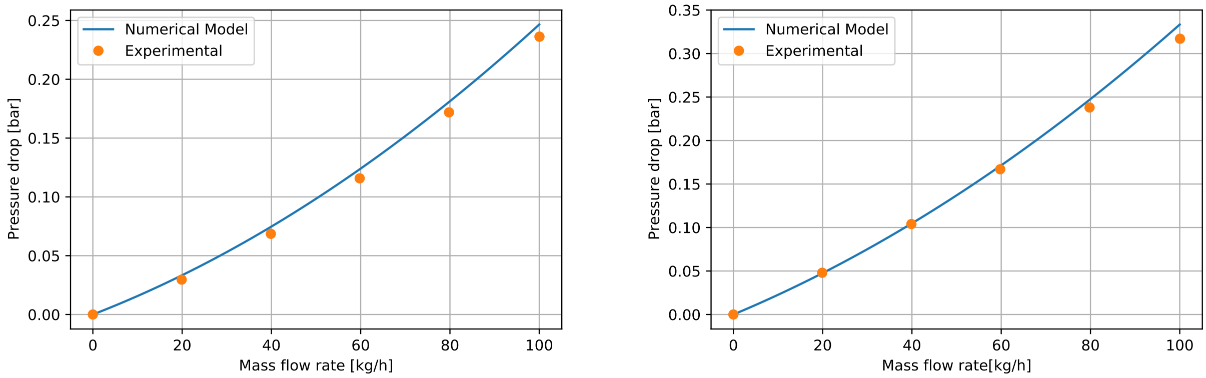


Figure 4. R^2 values for the fitting of LTC050 pressure drop results for different values of Ergun's Constant

This value for c_E was then used to predict the pressure drop results for the other regenerator, LTD081, obtaining an R^2 value of 0.995. The resulting numerical pressure drop profiles for both regenerators along with the experimental results are shown in Figs. 5.a and 5.b. The numerical values calculated are in good agreement with the experimental data, showing that the value obtained for Ergun's constant is a good estimate for this kind of geometry, hydraulic diameter and porosity.

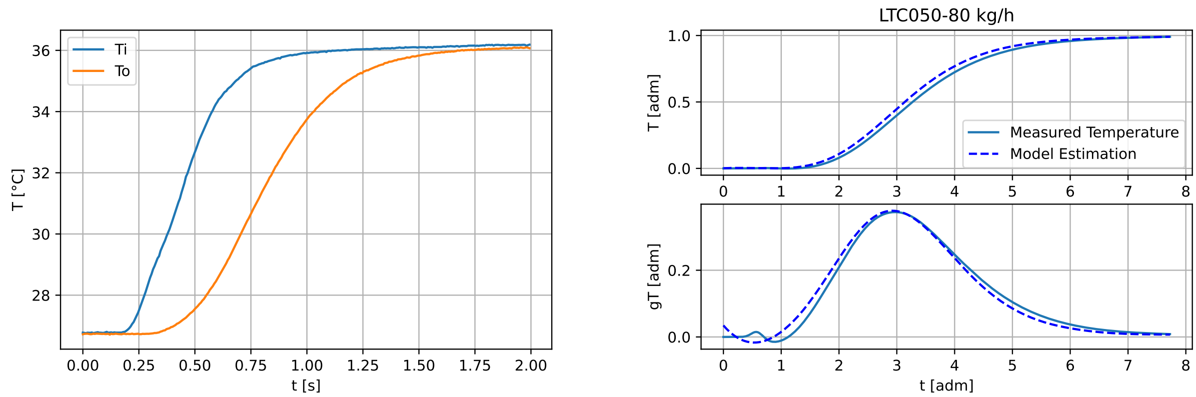
The single-blow tests were performed with a controlled temperature span that ranged between temperatures which were distant enough from the Curie temperature of the material to avoid phenomena associated with the magnetic phase change. The regenerators were submitted to a 10°C span (i.e., the step change in the inlet temperature was of ± 10°C), with regenerator LTC050 being submitted to a heating temperature step (i.e. the inlet temperature step was 10 °C higher than the initial temperature) while regenerator LTD081 was submitted to a cooling temperature step. This is illustrated in Figs. 6.a and 6.c, which show the experimental profiles of the inlet (T_i) and outlet (T_o) temperatures of both regenerators during the temperature step.



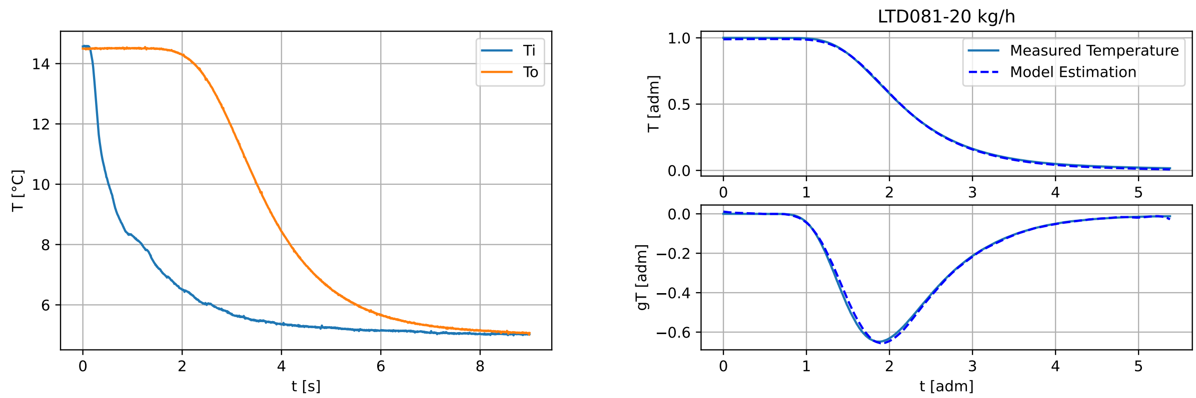
(a) (b)

Figure 5. Experimental and numerical values of pressure drop for regenerators (a) LTD050 and (b) LTC081.

In both regenerators, the single blow tests were performed under different mass flow rates varying from 20 to 80 kg/h. Different values of NTU were then used to solve Eqs. 3 and 4 and the value in which the calculated outlet temperature profile had the best fit with the data according to the gM method was determined to be the correct one. Examples of the curve fitting of both the temperature profile and its the derivative at the outlets are shown in Figs. 6.b and 6.d.



(a) (b)



(c) (d)

Figure 6. Inlet (T_i) and outlet (T_o) temperature profiles during the single blow tests for regenerators (a) LTC050 and (c) LTD081. Comparison and experimental outlet temperature profiles for regenerators (b) LTC050 at a mass flow rate of 80 kg/h and (d) LTD081 at a mass flow rate of 20 kg/h. The value of NTU that best fitted the data was of 2.6 in (b) and 12.5 in (d).

After the NTU value was determined, the Nusselt number could be calculated using the data shown in Table 1 and the following equations:

$$NTU = \frac{hA}{\dot{m}c_{\mathrm{p}}} \tag{5}$$

$$Nu = \frac{hD_{\mathrm{h}}}{k_{\mathrm{f}}} \tag{6}$$

where h is the interstitial heat transfer coefficient, A is the interstitial heat transfer area, $\dot{m}$ is the mass flow rate, c_{p} is fluid's the specific heat, D_{h} is the hydraulic diameter and k_{f} is the fluid's thermal conductivity.

The results for the NTU as a function of the Reynolds number are shown in Fig. 7. Regenerator LTC050 was submitted to single blow tests twice and thus has twice as many points than LTD081. It can be seen that the results for both regenerators hovered at slightly lower values than the Nusselt number for a triangular microchannel with a constant wall temperature, 2.49 (Bergman *et al.*, 2011). This difference could be explained by inherent uncertainties of the experiment and errors in the estimation of the heat transfer area, which was calculated assuming the channels had the shape of a perfect equilateral triangle which was not the case. Regarding the relation between the Nusselt number and the Reynolds number, the value of the Nusselt number for regenerator LTC050 seems to slightly decrease with the Reynolds number, while the results for LTD081 are the opposite. The changes, however, are fairly small and might again be explained by the uncertainties in the experiment and heat transfer area. This seems to indicate that the Nusselt number is in fact not affected by the Reynolds number (Re < 120), which again is the expected behaviour of an equivalent triangular microchannel.

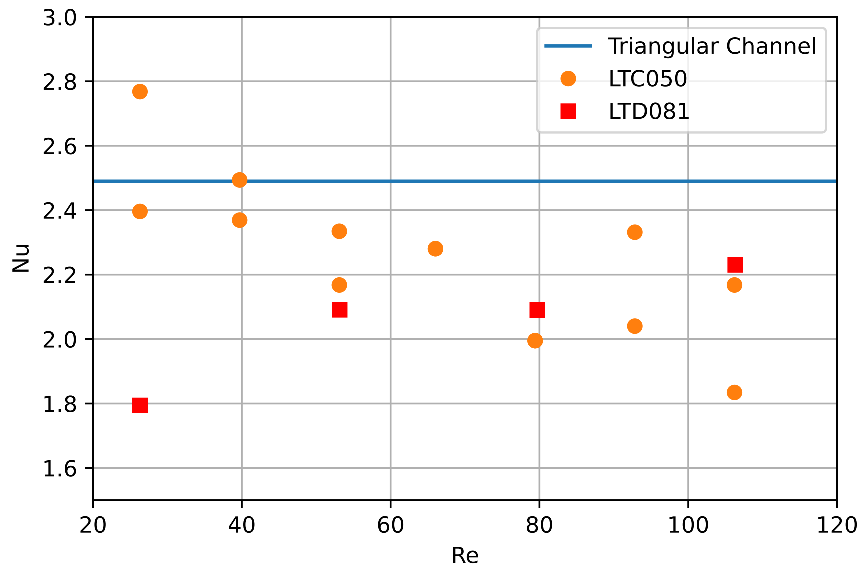


Figure 7. Nusselt number results as a function of the Reynolds number for both regenerators along with the Nusselt number for a triangular microchannel with a constant wall temperature for reference.

5. CONCLUSIONS

Two La-Fe-Si triangular microchannel regenerators were submitted to both pressure drop and single blow results in order to describe their thermohydraulic behaviour. Through the pressure drop results, an Ergun's constant of 0.17 was found to describe the first regenerator, LTC050. When this value was used to predict the pressure drop of the second regenerator, LTD081, the results showed a good agreement with the experimental data (R^2 = 0.995) indicating that this value is a good estimation for this kind of geometry, hydraulic diameter and porosity. Through the single blow tests, the Nusselt number as a function of the Reynolds number was found for both regenerator and was found to be very close, although slightly lower, than the one expected of a microchannel triangular channel with constant wall temperature, 2.49. This difference may be attributed to possible errors in both the experiment and the estimation of the heat transfer area. The Nusselt number also did not seem to be greatly affected by the Reynolds number, though both regenerators' Nusselt number did show a slight tendency to either increase or decrease with the Reynolds number. These changes, however, were fairly small and can again be attributed to errors in the experiment and the heat transfer area.

6. ACKNOWLEDGEMENTS

Financial support from CNPq, FAPESC, CAPES, CODEMGE and the EMBRAPII Unit Polo/UFSC is duly acknowledged.

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