Friction Factor And Regenerator Effectiveness In An Oscillating Gas Flow

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Abstract. This paper presents an experimental work to characterize the dynamic operation of a metal regenerator crossed by dry compressible air alternating flow. Unsteady dynamic measurements concern the pressure, velocity and temperature of the gas at the ends and inside the channels of the regenerator. The regenerators are tested under isothermal conditions and thermal axial temperature gradient. Results lead to the determination of the friction coefficient as well as the regenerator effectiveness. We also point out that the most relevant parameter to understand their evolutions is the oscillating Reynolds number.

Introduction. Regenerative cycle machine, such as Stirling cycle engines or cryocoolers, employ a thermal regenerator [1-3]. It absorbs the heat from hot gas and discharges the stored heat to the cold gas in oscillating flow between hot and cold space. The thermal and hydrodynamic irreversibilities in the regenerator which play crucial roles with respect to the efficiency of the Stirling cycle are poorly understood. Thus, regenerators are studied separately to characterize them and better understand their influence on an oscillating flow [4-8]. We present experimental investigations on the effects of regenerator porosities on its friction coefficient and effectiveness in a periodically reversing flow and for a wide range frequencies flow. Whereas most of the previous studies [4-8] analyze their evolution regarding the maximum Reynolds number, the wide parameters range investigated leads us to suggest to prefer the oscillating Reynolds number. In a second part, the regenerator effectiveness is estimated based on a model [9] using experimental temperatures measurements. Once again, oscillating Reynolds number seems to be a more relevant parameter for a regenerator effectiveness model.

Description of experimental set-up.

The schematic drawing of the experimental setup is shown in Fig.1. It is designed to investigate the characteristics of an oscillating flow in regenerators.

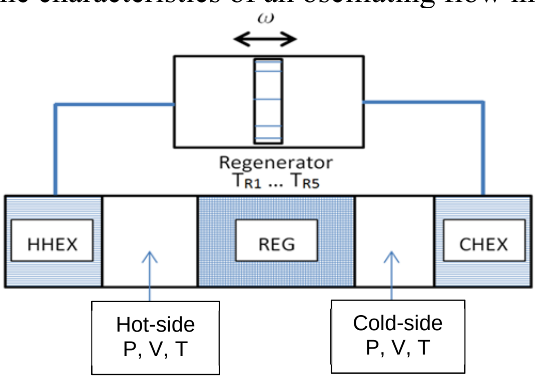
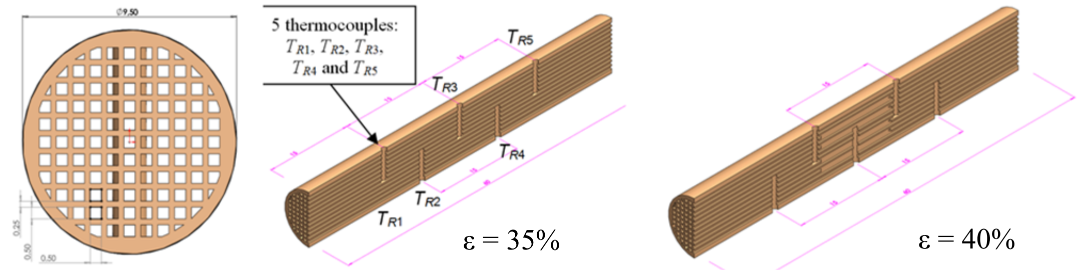


Figure.1 Scheme of the experimental bench for regenerator test

- HEX: Heat exchanger
- CEX: Cold Exchanger
- REG: Regenerator

Five major parts composed the experimental setup: a hot exchanger and a cold exchanger, a regenerator, a compression cylinder, a piston and a crankshaft. The reciprocating motion of the working gas (air) is generated by the motion of the piston in the compression cylinder. The piston motion is leaded by a crankshaft driven by a variable speed DC electrical motor. This electrical motor enables frequency up to 20 Hz. Two flexible tubes allow the working gas to pass from the compression chamber to the test section. At each side of the test section are Air/Water heat exchangers, a cold and a hot one. The regenerator is sandwiched between 10 mm diameter steel tubes connecting it to the exchangers.

Test section and instrumentation. Three regenerators have been studied. All are 316L stainless steel porous matrix. They have an outer diameter D_{reg} of 9.5 mm and a length of 60 mm. Their porosities vary from 30% to 40%. Regenerators are manufactured thanks to Direct Metal Laser Sintering (DMLS) technique. Fig.2 shows the typical structure of those regenerators. Note that, as porosity is not a relevant parameter due to the difference in mesh structure, regenerator will be designated using number. It means regenerator 1 (reg1) has a 30% porosity, regenerator 2 (reg2) matches the 35% porosity regenerator and the 40% porosity regenerator is called regenerator 3 (reg3).



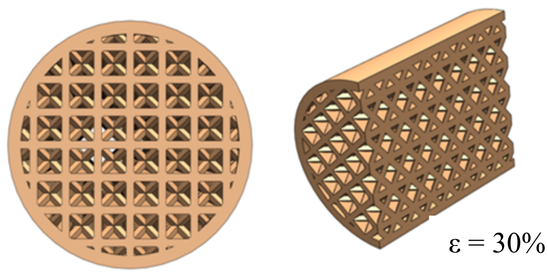


Figure.2 Drawings of the different regenerators tested.

- 35 and 40% porosity regenerators (reg2 and reg 3 respectively) present straight channel.
- 40% porosity (reg3) has a looser mesh at its center.
- 30% porosity regenerator (reg1) presents a pyramidal mesh.

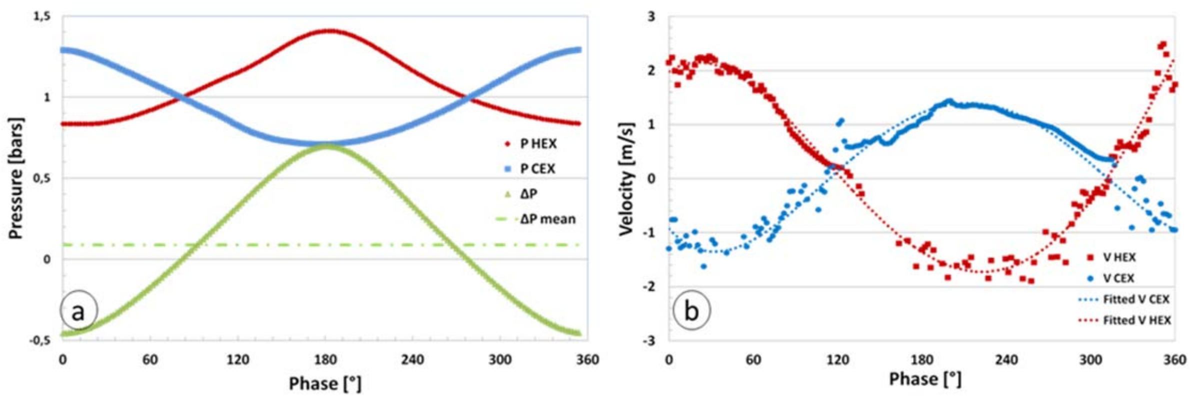
Two homemade 12.7 µm diameter K type (Chromel-Alumel) micro-thermocouples are placed in front of and after the regenerator. They were characterized under static and dynamic states [4]. Their accuracy is of ±0.1°C and their cut-off frequency f_c is closed to 30 Hz in forced convection. Five spots are manufactured on the regenerator to allow the introduction of those temperature sensors. The alternate flows have a frequency range between 0 to 6 Hz, implying no temperature correction as the cut-off frequency is higher than that of the flow ($f < f_c$). Local instantaneous pressures were measured using Kulite sensors (model XTL-140M-5BARA). Sensors were calibrated and placed at each side of the regenerator, one on the hot exchanger side (HEX) the other at the cold exchanger side (CEX). An electric proximity switch (SME-8-K-LED-24), mounted on the cylinder, was used to follow the crank angle. Its position gets the highest signal voltage output when the piston reached the top dead center. All those signals were collected by a National Instruments data acquisition card (SCXI-1000) and data processed using a Labview program. A hot-wire sensor (TSI, Model: 1201) was used for measurements of the instantaneous axial velocity at each side of the regenerator. The hot-wire sensor was calibrated by TSI IFA-300 system. The velocity signal was digitized by A/D converter card and data processed via Thermal-Pro software.

All signals are synchronized thanks to a National Instruments multifunction card (USB-6211 I/O 250 KHz).

To summarize, the experimental set up allows to test different regenerators (porosity, mesh) submitted to various oscillating flows (frequency, temperature gradient along the regenerators). Actually, pressure and temperature or pressure and velocities are investigated during an experiment. The first configuration leads to the friction factor investigation whereas the second one takes interest into regenerator effectiveness.

Results.

As explained above, the experimental data allow to investigate the friction factor (P and V measurements) or the regenerator effectiveness (P and T measurements for various configurations (porosity, regenerator mesh, flow frequency…) Examples of data measurements for a friction factor calculation (P and V; Figs 3a and 3b) and effectiveness determination (P and T; Figs 3a and 3c) are presented in Figure 3. These results have been obtained for regenerator reg1 (ε=30%; D_h=0,178 mm) and the actual maximum flow frequency (circa 5.8 Hz). Friction factors and effectiveness will be investigated for all 3 regenerators presented and frequency ranging from 0.2 Hz up to 5.8 Hz.



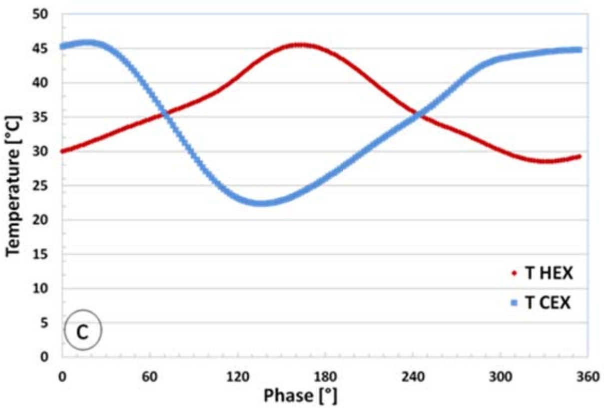


Figure.3 Evolution of different parameters at hot exchanger (HEX) and cold exchanger (CEX) sides of regenerator reg1 (ε=30%; D_h=0,178mm) versus phase for a 5.7Hz oscillating flow and no initial temperature gradient.
a: Pressures
b: Velocities
c: Temperatures

Friction factor. Figures 3a and 3b respectively present the pressure and velocities evolutions for a single period of the piston motion for regenerator 1 and a fluid frequency of circa 5.7 Hz. On figure 3a, the pressures on the hot exchanger side (HEX) and cold exchanger side (CEX) are plotted. The pressure drop ΔP is also given on Fig3a. The pressure drop allows us to determine its maximum value. It has been determined for a wide range of frequencies resulting. Instead of basically plot ΔP_{max} versus f, we use the oscillating Reynolds number (eq.1) which enables to also take the regenerator characteristics (porosity ε, mesh diameter D_{mesh}) into account.

$$Re_\omega = \frac{\rho \omega D_h^2}{\mu}. \tag{1}$$

The maximum pressure drop evolution is presented on Fig4a. It appears that for each regenerator, pressure drop tends to reach a limit which seems to depend more on the regenerator mesh geometry than on its porosity. One can observe that similar mesh regenerator (reg2 and reg3) have a similar pressure drop limit whereas regenerator 1 has a highest one.

During the same experiments, velocities are also measured. The velocities evolution at each sides of the regenerator (Fig4b) enables to determine the maximum velocities in the regenerator and like for drop pressure to obtain their evolution depending on Re_ω. This evolution is presented on Fig4b and conclusion similar to the pressure drop ones can be deduced. Maximum velocities tends to reach a limit value mainly dependant on the mesh geometry. Maximum velocities are complicated to measure. It results from turbulence that occurs at acceleration/deceleration transition moment that is also time of maximum velocity. However the limit is now lowest for regenerator reg1. That is physically logic as the pressure drop is higher in that configuration.

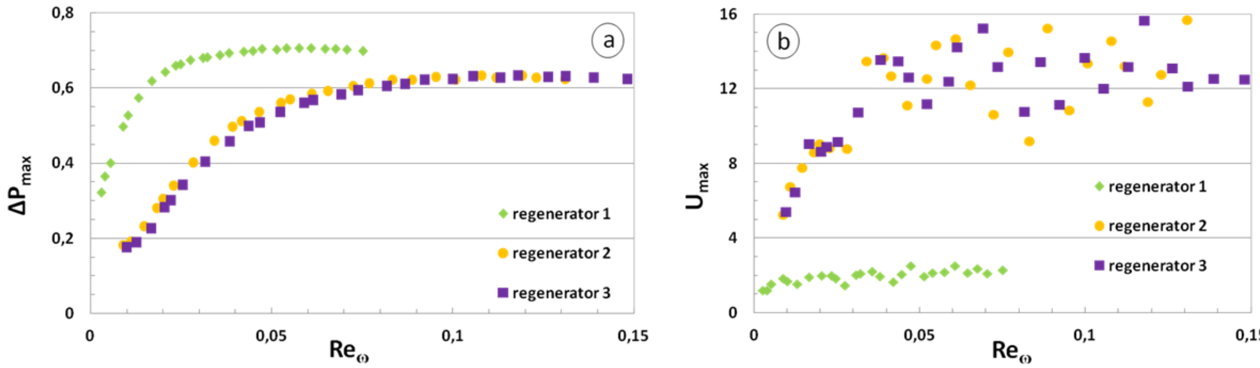


Figure.4 Evolutions of the maximum pressure drop (left) and the maximum velocities (right). Experiments have been conducted for reg1 (ε=30%; D_h=0,178 mm), reg2 (ε=35%; D_h=0,237 mm), reg3 (ε=40%; D_h=0,250 mm) and a wide range of frequencies (0.2 to 5.8 Hz).

The maximum pressure drops and maximum velocity results are useful for the determination of the friction factor as it is given by eq.1

$$C_f = \frac{\Delta P_{max} D_h}{\frac{1}{2} L\bar{\rho} u_{max}^2}. \qquad (1)$$

The other parameters needed are detailed in Table1.

Table.1 Parameters of the friction factor formulae and their determination formulas

Hydraulic diameter D_h	Period average density $\bar{\rho}$	Regenerator length L	Maximum gas velocity u_{max}
$\frac{V_{gas}}{S_{exch}}$	$\frac{1}{T}\int_0^{2\pi} \rho(\omega t)d\omega t = \frac{\sum_{i=1}^{n}\rho_i}{n} = \frac{1}{n}\sum_{i=1}^{n}\frac{P_i}{rT_i}$.	60mm	$\frac{u_{i\,max}}{\varepsilon}$.

Note that the hydraulic diameter is obtained thanks to the value of the gas volume and the exchange surface given by the CAD software used to design the regenerators.

The friction coefficients calculated for the 3 sets of experiments are presented in Fig.5. Regarding the previous results showing different behaviors depending on the mesh geometry, we plot separately regenerator 1's data (Fig5a). Once again results are plotted according to the oscillating Reynolds number. As shown on Fig.5, correlations have been deduced from our experimental results. Only the correlation for reg1 has been added on Fig.5 in order not to plot to many information on a single graph. All the experimental correlations found are summarized in Table.2.

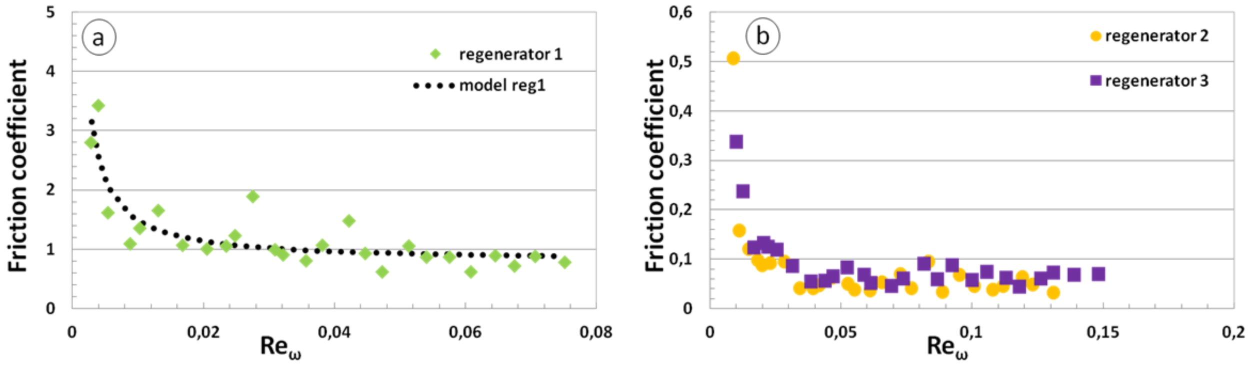


Figure.5 Evolutions of the friction factors for reg1 (a), reg2 and reg3 (b). Experiments have been conducted on a 60 mm long regenerator for 3 different porosities (30, 35 and 40%) and a wide range of frequencies (0.2 to 5.8 Hz).

Table.2 Experimental correlations for the friction coefficient

Regenerator	Classical correlation model	A	B
reg1 (ε=30%; D_h=0,178 mm)	$C_f = \frac{A}{Re_\omega} + B$	0.00689	0.791
reg2 (ε=35%; D_h=0,237 mm)		0.00279	0.00186
reg3 (ε=40%; D_h=0,250 mm)		0.00246	0.02962

Regenerator effectiveness. The regenerator effectinevess (E) as defined by Lee et al [9] depends on the average temperatures at each regenerator sides (T_{HEX} and T_{CEX}) during a half period. The formula to estimate effectiveness is

$$E = \frac{(\bar{T}_{HEX})_{in} - (\bar{T}_{CEX})_{out}}{(\bar{T}_{HEX})_{in} - (\bar{T}_{CEX})_{in}} \tag{10}$$

Where

$$(\bar{T}_{HEX})_{in} = \frac{\int_0^\pi T_{HEX}(\omega t)d\omega t}{\int_0^\pi d\omega t}; \quad (\bar{T}_{CEX})_{out} = \frac{\int_0^\pi T_{CEX}(\omega t)d\omega t}{\int_0^\pi d\omega t}; \quad (\bar{T}_{CEX})_{in} = \frac{\int_\pi^{2\pi} T_{CEX}(\omega t)d\omega t}{\int_\pi^{2\pi} d\omega t}$$

The average temperatures during half a period are determined from the temperature measurement. An example of temperature measurements is presented on Fig.6 (left) for reg1 submitted to a 67°C temperature gradient (T_{HEX}=79°C; T_{CEX} = 12°C) and to a 5.7 Hz oscillating flow frequency. On this graph one can see that due to compressible effect, temperature varies according to air density change i.e. if air is submitted to a compression or an expansion phase.

Note that due to compressible effects, the average temperature on each side of the regenerator ($\bar{T}_{HES} \approx 82$°C for hot side; $\bar{T}_{CES} \approx 21$°C for cold side) is higher than the heat exchanger temperature. In each experiment, average temperatures $(\bar{T}_{HEX})_{in}, (\bar{T}_{CEX})_{in}$ and $(\bar{T}_{CEX})_{out}$ are obtained thanks to results similar to those presented in Fig.6a. Experiments have been conducted only for regenerator 1 and for frequencies ranging from 1Hz to 6 Hz (frequency step of about 1Hz). The effectiveness calculated for those experiments are plotted on Fig.6 (right). It appears that effectiveness decreases with oscillating flow Reynolds number whatever the porosity is. The effectiveness decrease with oscillating Reynolds number is the same whatever the tested regenerator is. The arrangement of the experimental data suggests that highest effectiveness is obtained for small hydraulic diameter regenerator as well as low pulsation frequency.

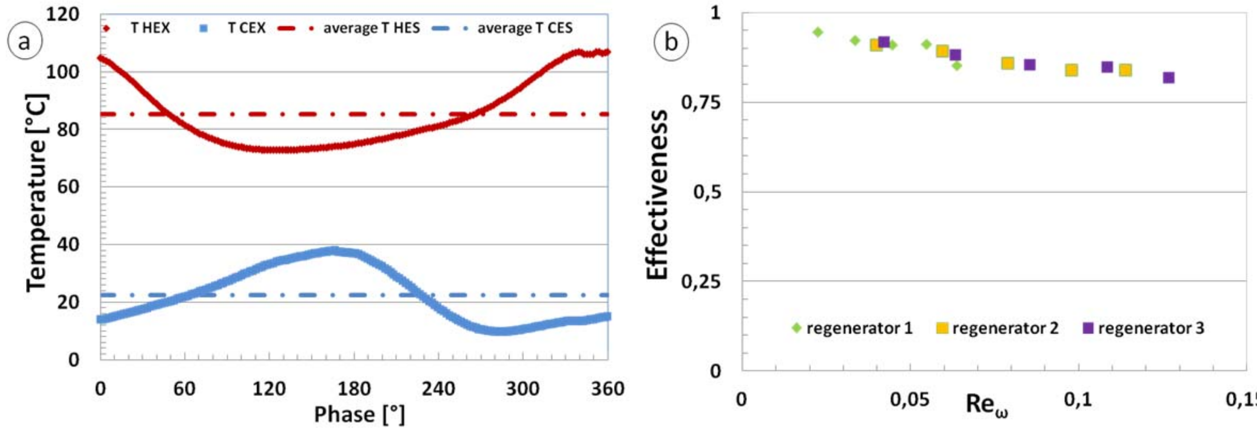


Figure.6 Example of the evolution of the temperature (a) for a period of a 5.7 Hz flow oscillating at each regenerator extremity ($\varepsilon = 30\%, D_h = 0{,}178\ \mathrm{mm}, L = 60\ \mathrm{mm}, T_{HEX} = 79°C$, $T_{CEX} = 12°C$) and evolution of the effectiveness (b) versus oscillating flow Reynolds number Re_ω in the different regenerators.

Conclusion.

Experiments have been conducted to investigate the behavior of regenerator submitted to an oscillating flow. Both isothermal and temperature gradient configuration along the regenerator have been tested. Different porosities as well as a wide range of flow frequency have been studied. During experiments temperature and pressure at each side of the regenerator are always recorded. Depending on the experiments, velocities are also measured at the same locations. By combining these different measurements, we determined the friction factor and the effectiveness of each tested regenerator for several frequencies. We have proposed to investigate the friction factor and effectiveness evolution as a function of the oscillating Reynolds number Re_ω. This choice enables to take into account simultaneously the flow characteristics (frequency) as well as the regenerator ones (hydraulic diameter). Correlations have then been proposed for friction factor. Fewer experiments have been realized to study effectiveness. Although, the first results presented here, suggest that once again, the oscillating Reynolds number is a relevant parameter for further correlations.

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