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EXPERIMENTAL STUDY AND MODELISATION OF A PULSE TUBE REFRIGERATOR.

A. Ravex, P. Rolland and J. Liang

CEA/DRFMC/SBT, BP 85X, 38041 Grenoble Cédex, France.

A test bench for pulse tube refrigerator characterization has been built. In various configurations (basic pulse tube, orifice pulse tube and double inlet pulse tube), the ultimate temperature and the cooling power have been measured as a function of pressure wave amplitude and frequency for various geometries. A lowest temperature of 28 K has been achieved in a single staged double inlet configuration. A modelisation taking into account wall heat pumping, enthalpy flow and regenerator inefficiency is under development. Preliminary calculation results are compared with experimental data.

INTRODUCTION

The refrigeration concept originally suggested by Gifford and Longsworth (1) is now commonly known as the basic pulse tube refrigerator. Mikulin et al. (2) have modified and improved the original concept by adding a buffer volume connected to the warm end of the pulse tube through an impedance : this is the orifice pulse tube refrigerator. A later improvment has been proposed by Zhu et al (3), introducing an impedance at room temperature between the pressure oscillator and the pulse tube, by passing part of the gas flow through the regenerator : this is the double inlet pulse tube refrigerator.

All these improvements, increasing the cooling capacity and therefore the lowest achievable temperature, makes the pulse tube refrigerator a very attractive system with no cold moving part.

We have undertaken an experimental characterization and a thermal modelisation of the pulse tube refrigerator to get a better understanding and a practical tool for system sizing and efficiency calculation.

DESCRIPTION OF THE EXPERIMENTAL SET UP

The schematic of the experimental set up is shown on figure 1.

The pressure oscillation is generated by an helium compressor connected to the pulse tube refrigerator either by an electromagnetic 3 way solenoid valve or by a rotating distributor with adjustable cycle frequency (0-20 Hz).

The regenerator consists of a stainless steel tube with 0.5 mm wall thickness, 18 mm inner diameter, filled with 1400 discs of 180 mesh stainless steel wire gauze discs.

Three pulse tubes made of stainless steel tube 200 mm long whose inner diameter are 19.5, 14 and 10 mm have been tested. At both end of the pulse tubes about 40 copper gauze discs are brazed for flow straightening and heat exchange. At room temperature the heat exchanger is water cooled. At cold end of the pulse tube, the temperature is measured either with a platinum (100 Ω) or a carbon thermometer. A heating resistance is also provided for cooling power measurements.

At both ends of the regenerator, thermocouples (Type E) and piezoresistive pressure transducers are used to follow the temperature and pressure oscillations of cycle helium gas.

At room temperature a buffer volume is connected to the pulse tube through an adjustable needle valve V1. A by pass adjustable needle valve V2 is also inserted between the warm ends of the regenerator and of the pulse tube. These two valves allow for all types of configurations : basic pulse tube (V1 and V2 closed), orifice pulse tube (V1 opened, V2 closed) and double inlet pulse tube (V1 and V2 opened).

EXPERIMENTAL RESULTS

The ultimate cold end temperature with no net cooling power has been measured for the three pulse tube diameters as a function of the pressure wave frequency for various opening of the needle valves V1 and V2. The experimental results obtained for basic, orifice and double inlet pulse tube configurations are reported on Figure 2. These curves correspond to the optimized needle valves adjustments leading to the lowest cold end temperatures. A lowest temperature T = 28 K has been obtained in the double inlet configuration for the 14 mm inner diameter pulse tube at a frequency of 3 Hz, with a pressure wave amplitude $\Delta P = 7$ bar (mean pressure $\overline{P} = 12$ bar).

The general shape of all these curves is quite similar with an optimal frequency corresponding to a minimal temperature. This can be easily explained qualitatively. First, when the pressure wave frequency increases at low values, the increase of the cooling power leads to a temperatures decrease. The mass flow rate to be furnished by the compressor and to be treated by the regenerator increases with the frequency. For high frequencies, the increasing pressure drop and the decreasing efficiency of the regenerator leads to a decrease of net cooling power and consequently a temperature increase.

Cooling power measurements reported on Figure 3 have been performed in all configurations for frequencies and valve opening adjustments corresponding nearly to the lowest achieved temperature with no net cooling power. It is worth noting the interest of the double inlet configuration for increasing the thermal performances.

We have studied the influence of the pressure oscillation amplitude for various frequencies and valves adjustments. The cooling power first logically increases with the amplitude of the pressure wave. But a saturation effect occurs (for our pulse tube volumetry typically when $\Delta P \geq 4\text{-}5$ bar) when the swept mass flow rate in the regenerator induces inefficiency thermal losses greater than the gross cooling benefit.

The influence of the mean pressure has also been studied. In the explored range of variation (6-15 bars) no important effect has been observed on the no net cooling ultimate temperature but an optimal mean pressure can be experimentally defined in cooling power measurements again resulting from a balance between performance increase with the mass flow rate increase due to mean pressure increase and the limitation of the regenerator capacity.

No clear influence of pressure wave shape (sinusoïdal or square) has been observed.

MODELISATION

The experimental results obtained with the test bench show that there is a strong dependance of the optimal operation of a pulse tube refrigerator with parameters such as geometry of the pulse tube, efficiency of the regenerator, flow impedance of the orifice and bypass valves, frequency and amplitude of pressure oscillations. To be able to design a pulse tube refrigerator capable of specified performances (cooling temperature and power) and to estimate its thermodynamical efficiency, there is a need for a modelisation taking into account all the above mentionned parameters. We have undertaken the developement of such a model. The detailed description of this calculation will be presented elsewhere.

The main characteristics of our modelisation are :

- Heat transfer by wall heat pumping effect, which is the main cooling process in the basic pulse tube, is taken into account and calculated with the empirical formula proposed by Longsworth (4).
- Enthalpy flow analysis, as described by Radebaugh et al (5), is used to describe and calculate the dominant cooling process in orifice and double inlet pulse tube, assuming a sinusoidal or square pressure wave.
- Conduction through the pulse tube and regenarator stainless-steel wall is taken into account as a thermal loss. Axial conduction through the regenerator metallic screens is also taken into account.
- Regeneration inefficiency thermal losses are also taken into account by a regenerator calculation program developed in our laboratory using the theoretical correlations for heat transfer and pressure drop through metallic screens proposed by Kays and London (6).

Results obtained with our model are compared on figure 4 with experimental results. No adjustable parameter is used, calculation input are the geometrical and physical characteristics of the regenerator and of the pulse tube and the pressure variations experimentally measured.

We find a very good agreement in the general shape of the temperature variation with frequency. In particular the optimal value of the frequency is well reproduced. It means that the regenerator inefficiency which is the physical reason to obtain an optimum is correctly taken into account in our model. It remains a slight discrepancy in the absolute value of the temperature. There are many likely explanations : uncertainty in gas heat transfert through the thermal boundary layer thickness, validity of Kays and London correlations, axial thermal losses in the regenerator matrix ... All these points will be more precisely investigated in the forthcoming development program.

CONCLUSION

We have built an experimental set up well adapted for pulse tube refrigerator characterization. A lot of experimental results have been collected showing the influences of the main parameters. A modelisation program is under development and first calculation results are in good agreement with experimental data.

The next step will be to improve the modelisation and to use it for the design of an optimised pulse-tube refrigerator using an oscillating pressure wave generator instead of a compressor with distribution valve. This will make easier the experimental determination of the coefficient of performance of the pulse tube refrigeration. One of our goal is also to develop a long-life pressure wave generator.

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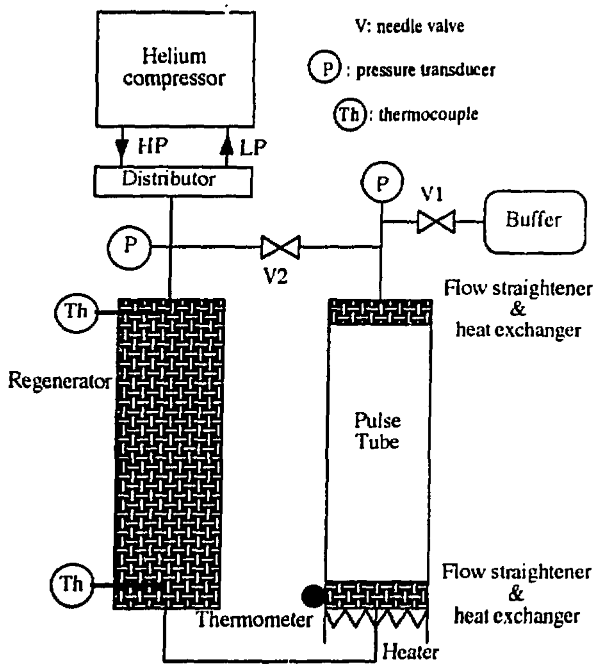

Figure 1: Experimental set-up

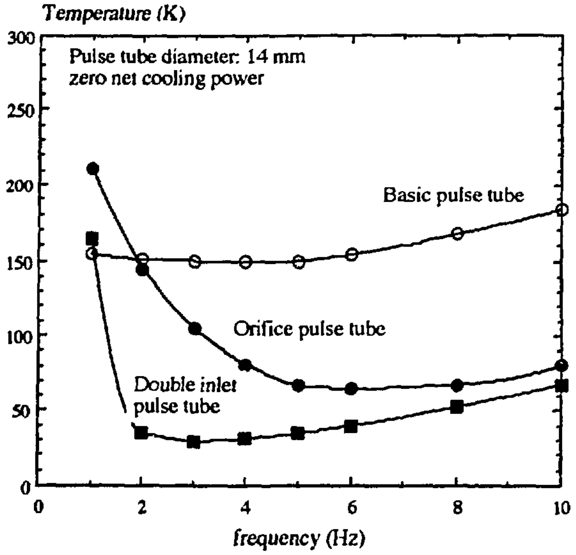

Figure 2: Ultimate temperature versus frequency

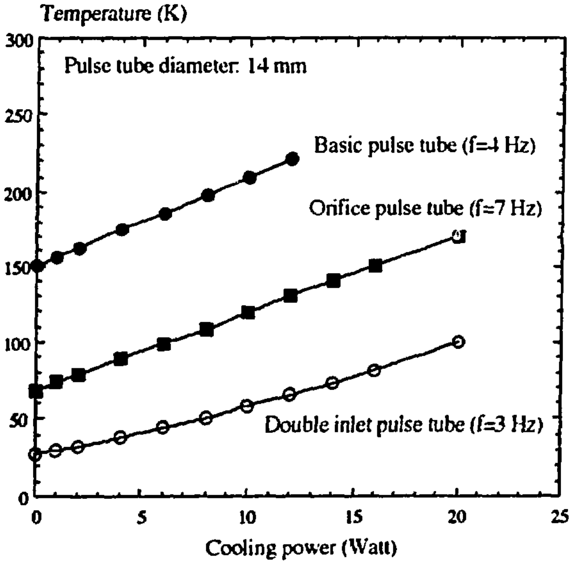

Figure 3: Temperature versus cooling power for various configuration

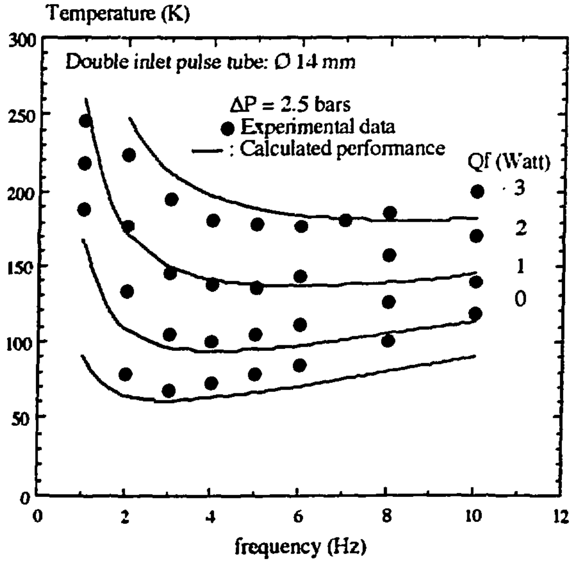

Figure 4: Comparison between experimental and calculated performance