Heat transfer in porous media applied to liquid rocket engines

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Abstract

Advances in space propulsion require the use of new materials. The Institute of Space Propulsion at DLR Lampoldshausen (Germany) has been investigating for the application of porous materials in liquid rocket engines. The development of transpiration cooling for combustion chamber is based on such materials in a configuration where hydrogen flows through the wall. Another application is injector heads which offer a better homogenization of the propellants. The efficiency and reliability of such components depend on the permeability of the flow through the porous structure and the heat exchange between the fluid and the porous material. A description of those physical processes is necessary.

A new experimental set up has been developed with requirements to reproduce and to control flow and heat transfer in a porous material at high temperature, high pressure and a wide range of mass flow. It gives the possibility to study the influence of the properties and the structure of the porous material, the properties of the fluid, the parameters of the flow and the heat loads. Appropriate measurements will be made in the fluid and on the material to determine the pressure loss and the thermal exchanges in the porous sample. The main objective is to develop appropriate models of permeability and heat transfer for real rocket components.

This work presents the investigation made to develop such an experimental device. The design and the methodology of the measurements chosen are explained. First experimental results and CFD analysis are also given.

1. Introduction

For future liquid rocket engine, high capacity combustion chambers will be necessary. The resulting high pressure and high heat loads on the wall of the combustion chamber require alternative cooling method instead of the actual regenerative cooling. Transpiration cooling where an amount of fuel (LH2) passes through the wall into the combustion chamber is a promising technique. DLR is investigating for the use of porous materials, nonmetallic and metallic, for such applications but knowledge about the flow and the thermal distribution is still necessary.

Coaxial injectors are mainly used in LOX/H2 rocket engine like in the Space Shuttle Main Engine or the Vulcain II. Liquid oxygen is injected through an inner tube (20-30m/s) while the fuel (LH2) is introduced with much higher velocity 200-400m/s through a concentric annulus gap. Those injectors present good atomization and mixing, enable relative combustion stability and efficiency but have problems with throttleability, manufacturing costs, recess, tapering and wall interaction. The concept of porous faceplate seems to be a good alternative. It enables the injection of the fuel through the porous plates and the LOX through tubes using a small amount of fuel for the cooling.

The efficiency of transpiration cooling and porous injection is dependent on the permeability of the flow in the porous structure and on the heat exchanges between the solid and the fluid. Permeability is described by several models which depend on the Reynolds number such as Darcy, Forchheimer, Burke Plummer models [1]. The heat transfer occurs by convection and radiation.

Due to the flow mixing and the important surface area with coolant, porous structures appear to be an effective technique to increase heat transfer. Heat transfer in porous media has been studying experimentally and numerically for many years due to its importance in applications in many fields.

Jiang et al. [7-9] showed experimentally and numerically that the convection heat transfer is greatly intensified in case of water or air in non-sintered packed beds. A criterion was defined to describe the effect of particle diameter on the heat transfer coefficient [8]. Jeigarnik et al. [2] experimentally investigated convection heat transfer of water on flat plates and in channels filled with porous material such as sintered spherical particles, nets, porous metal, and felts considering different thickness (0.86–3.9 mm) and particle diameters (0.1–0.6 mm). They found that the porous media increases the heat transfer coefficient (5–10 times) although the hydraulic resistance was increased even more. Hwang and Chao [6] focused on convection heat transfer of air in 5 · 5 · 1 cm sintered porous channels. They found that the forced air heat transfer coefficient was increased from 100 to 5000 W/(m2 K). They also showed that the conventional thermal equilibrium one-equation model overpredicts the Nusselt number for sintered porous channel flow. In theoretical and numerical investigations of convection heat transfer in porous media, two different models have been used for the energy equation: the local thermal equilibrium model and the local thermal nonequilibrium model.

This article present a description of the experimental set-up developed at DLR Lampoldshausen to reproduce and measure permeability and heat transfer in porous media. A CFD numerical model and the results obtained are also presented.

2. Experimental method

An experimental set-up has been tested at DLR Lampoldshausen for the measurement of heat transfer in porous materials at high pressure up to 40bar and high temperature up to 700K. The principle is to heat a porous sample, to create a flow across the sample and to measure the difference of enthalpy of the fluid between the two states at the inlet and the outlet.

Figure 1 gives the description of the experimental set up. The sample has conical shape to insure good contact with the heater and to avoid any leakage.

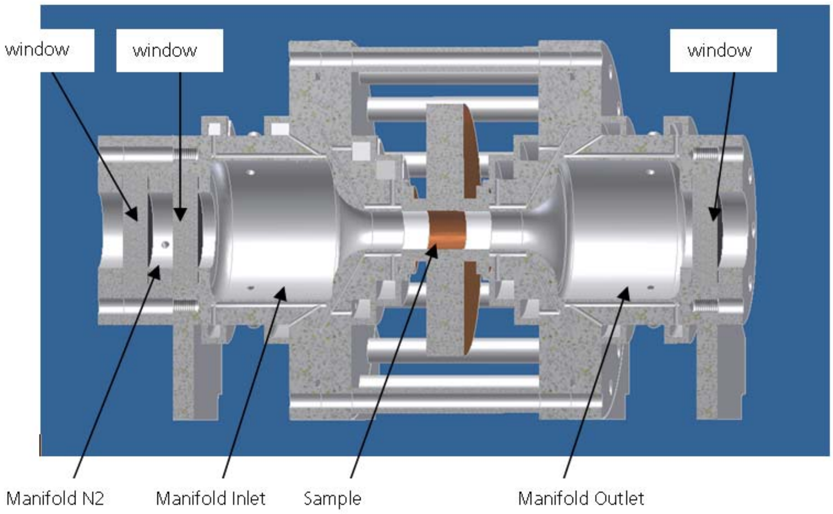

Figure 1: Structure of the experimental set-up

The heater device is a copper cylinder manufactured by Thermocoax. It has three heating elements around the outer surface connected to three thermocouples. It delivers a maximal power of 8.4kW and a maximal temperature of 700K, corresponding to the limit of the structural stability of copper. A controlling device from Gröppler enables thanks to a PNID controller to reach the whished temperature. A thermal insulation is used around to decrease heat losses.

Two valves are used to control the mass flow and the pressure drop across the porous sample according to Darcy´s law. The manifolds at the inlet and at the outlet help the velocity homogenisation of the fluid and the measurement of the total temperature and the total pressure. The difference pressure is also measured with more accuracy.

The measurement on the porous sample includes the temperature gradient across the outer surface of the sample thanks to 11 thermocouples. Those thermocouples are placed at 1mm in the copper heater to avoid any leakage. Infrared measurements are also considered to estimate the temperature gradient at the inlet section and at the outlet section of the sample. The IR-camera manufactured by Variocam is defined by a spectral range of 7.5-14µm with an accuracy of 1.5K between 0 and 100°C and 2% for temperatures above 100°C. Windows made off Zinc sulfide are used for the optical measurements separating the gas in the manifolds and the ambient atmosphere where the IR-cameras are placed.

To avoid condensation on the window during cold tests conditions, a GN2 manifold (2bar) is expected with an additional window at the inlet side. At both sides, a tube made off Polyvinyl chloride is fixed on the corresponding ring using a silicone sealing on the interface between the two bodies. This ring is supplied with nitrogen. Twelve holes drilled on the ring direct a flow of heated nitrogen to the surface of the window. Nitrogen is then droven inside the Polyvinyl chloride tube to the atmosphere. This configuration enables to reject the atmosphere from the window; therefore any possible condensation of the water contained in the atmosphere on the cold window.

The temperature at 1mm from the inner surface of the manifold is measured using thermocouples. This structure made of steel is cooled with water flowing in 16 channels to prevent high thermal loads and to keep the inlet surface of the manifold at constant temperature. Water is provided from a tank pressurized at 6bar with nitrogen.

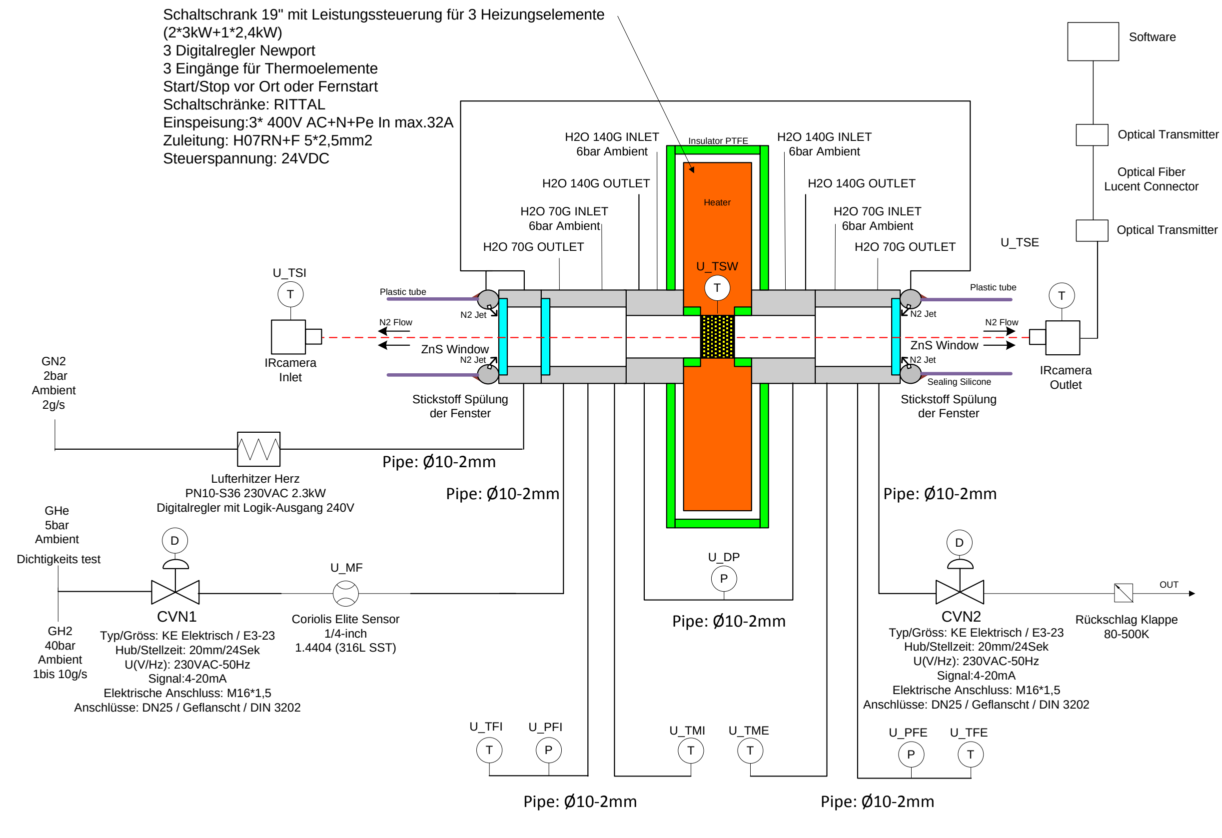

Figure 2: Flow diagram

The devices and the measurements in the fluid and on the sample enable the determination of the parameters of the flow and the thermal gradient in the solid sample. Several configurations for the tests can then be fixed to analyze the influence of the properties and the structure of the porous material, the properties of the fluid, the parameters of the flow and the heat loads.

The heat transfer in the porous sample in case of forced convection occurs with convection and radiation. The modelization of those phenomenons in macroscopic and microscopic scales has to be developed in this specific case but the measurement made enables the estimation of the heat transfer.

The gas is submitted to different heat exchanges: in the manifold at the inlet, in the manifold at the outlet and in the porous sample. Each heat exchange is then estimated:

$$Q_{M\_Inlet} = Q_{M\_Inlet\_radiation} + Q_{M\_Inlet\_convection} \qquad \text{Eq. 1}$$

$$Q_{M\_Outlet} = Q_{M\_Outlet\_radiation} + Q_{M\_Outlet\_convection} \qquad \text{Eq. 2}$$

$$Q_{Porous} = Q_{Porous\_radiation} + Q_{Porous\_convection} \qquad \text{Eq. 3}$$

The difference of enthalpy of the fluid is defined:

$$\Delta h = \dot{m}Cp(T_{Inlet} - T_{Outlet}) \qquad \text{Eq. 4}$$

The heat transfer in the porous sample is then:

$$Q_{Porous} = \dot{m}Cp(T_{Inlet} - T_{Outlet}) - Q_{M\_Inlet} - Q_{M\_Outlet} \qquad \text{Eq. 5}$$

3. Numerical simulation

A 3D CFD model has been developed with the software Ansys Workbench Fluent. The geometry (Figure 3) is a reproduction of the experimental set up including a fluid part and a porous part. The wall of the duct (manifold and connector) is supposed adiabatic. The wall of the porous part is set at the value of the heating temperature. The inlet boundary defines the mass flow rate while the outlet one the pressure.

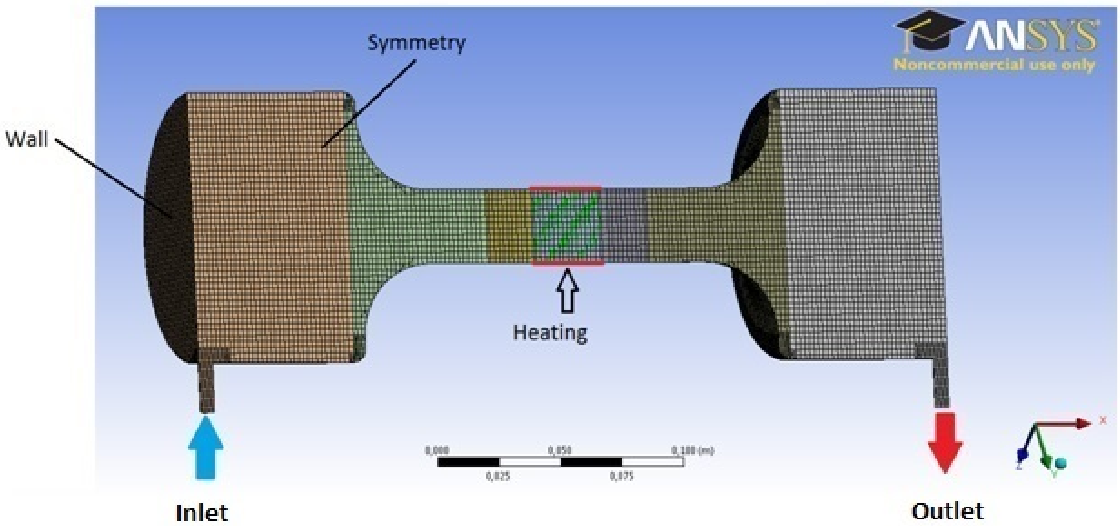

Figure 3: 2D axisymmetric CFD model

In this approach, we assume the fluid as an ideal gas and a turbulent flow described by the k-epsilon model (applicable for a wide range of flows). The heat transfer occurring in the porous part between the solid structure and the fluid is supposed to obey to the thermal equilibrium model using the energy transport equation as defined in Eq.

6. This model can be called as a one-temperature model because it considers in this porous domain the solid and the fluid with the same temperature, which not physically true.

$$-\frac{\partial}{\partial t}(\gamma\rho_f E_f + (1-\gamma)\rho_s E_s) + \nabla.(\vec{v}(\rho_f E_f + p)) = \nabla.[k_{eff}\nabla T - (\sum_i h_i J_i) + (\bar{\bar{\tau}}.\vec{v})] + S^h{}_f \qquad \text{Eq. 6}$$

E_f =total fluid energy
E_s =total solid medium energy
γ =porosity of the medium
k_{eff} =effective thermal conductivity of the medium
$S^h{}_f$ =fluid enthalpy source term
J_i =diffusion flux
$\vec{v}$ =fluid velocity
$\bar{\bar{\tau}}$ =constraints tensor
h = enthalpy

The flow through a porous sample is described using the Forchheimer model with two parameters α and β:

$$-\frac{\partial p}{\partial x} = \frac{\mu}{\alpha}U + \frac{\rho}{\beta}\left\|\vec{U}\right\|U \qquad \text{Eq. 7}$$

p	=	Pressure (Pa)
μ	=	Dynamic viscosity (Pa s)
ρ	=	Density (kg/m^3)
α	=	Darcy permeability (m^2)
β	=	Forchheimer permeability (m)

Numerical analysis has been performed in case of sintering bronze SIKA-B 100. This material has a homogeneous structure made of spherical particles. Hydrogen is used as a fluid at temperature of 277K and with a mass flow rate of 2g/s. The outlet boundary condition is set at atmospheric pressure. The temperature load on the sample is fixed at 469K.

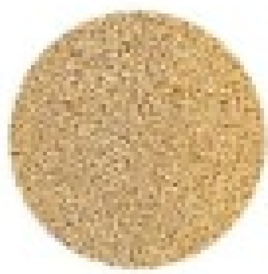

Figure 4: Porous sintering bronze SIKA-B-100

Material	Porosity ρ	$\alpha(10^{-12}m^2)$	$\beta(10^{-7}m)$	$\lambda(W/(mK))$
SIKA-B-100	0,42	127	406	387.6

Table 1: Properties of SIKA-B 100

Figure 5 gives the results obtained for the velocity, the pressure, the density and the temperature profile resulting in the fluid and the porous section. The heated porous sample affects the flow: pressure drop through the sample, decrease of the density and increase of the velocity resulting from the thermodynamical expansion of the fluid.

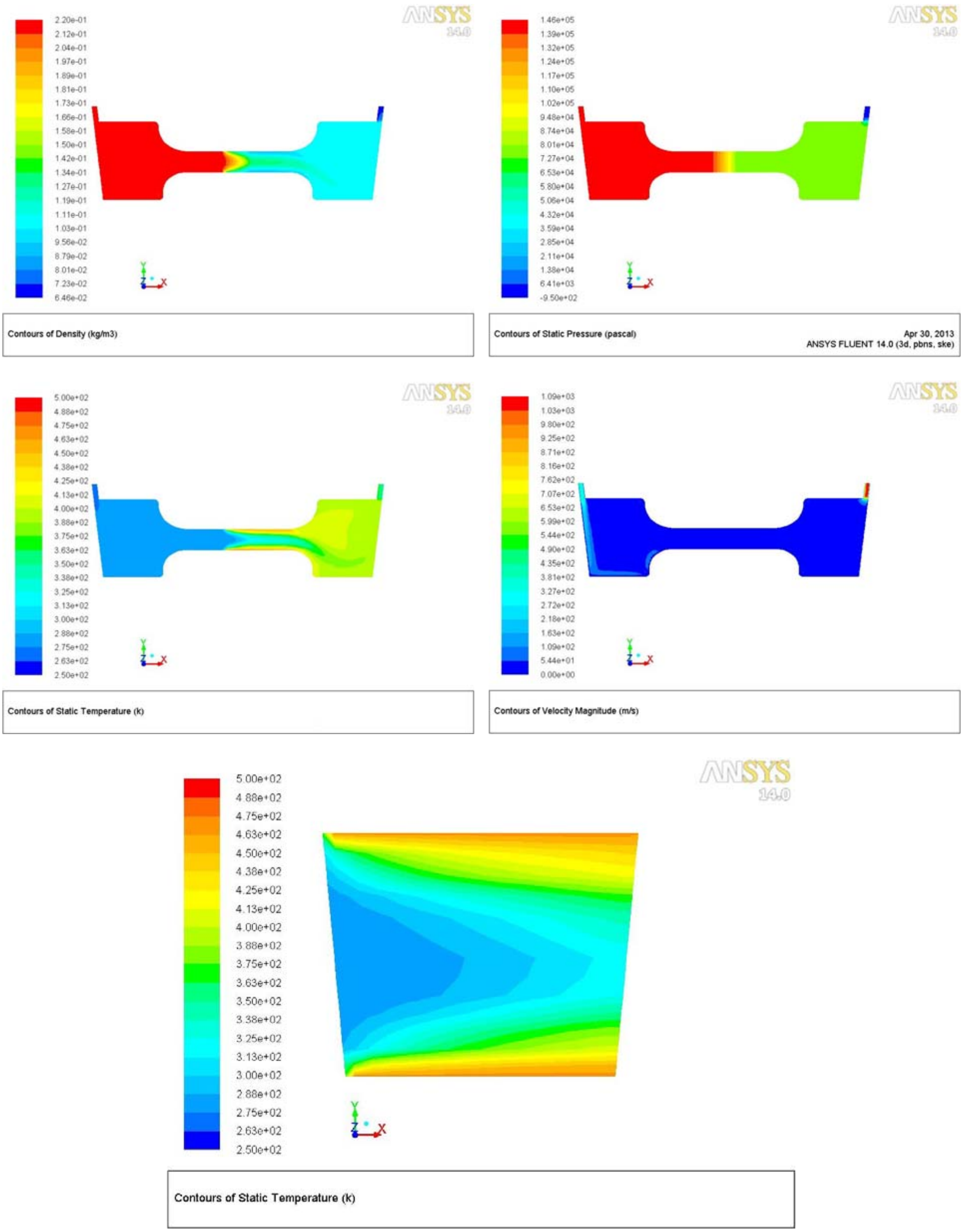

Figure 5: CFD analysis SIKAB100

4. Experimental results

A test campaign was driven for SIKA-B-200 at test bench P61 at DLR Lampoldshausen. Initially, the temperature of the heater is set at constant value until reaching an equal repartition of the temperature inside the porous structure. Then a sequence of 55 opening levels of the valves is applied to allow a flow at different mass flow and pressure drop. At each step of the sequence, stationary conditions are supposed to be reached. The different measurements are then recorded. At all, the tests were made for three levels of heating temperature (400, 450 and 500K) using gaseous nitrogen and hydrogen both at ambient and cryogenics temperatures. The pressure of the providing gas was fixed at 40bar.

Figure 6 shows the results for the pressure drop represented as a function of the mass flow. Higher the mass flow higher the pressure drop DP. The heating temperature doesn´t seem to have any significant influence on the pressure drop.

Figure 7 is a representation of the temperature difference of the fluid between the inlet and the outlet as a function of the mass flow. It is remarkable that in case of cryogenic fluids (GH2cold and GN2cold) the temperature drop increases with the mass flow while for ambient fluid (GH2ambient and GN2ambient) the temperature drop decreases with increasing mass flow.

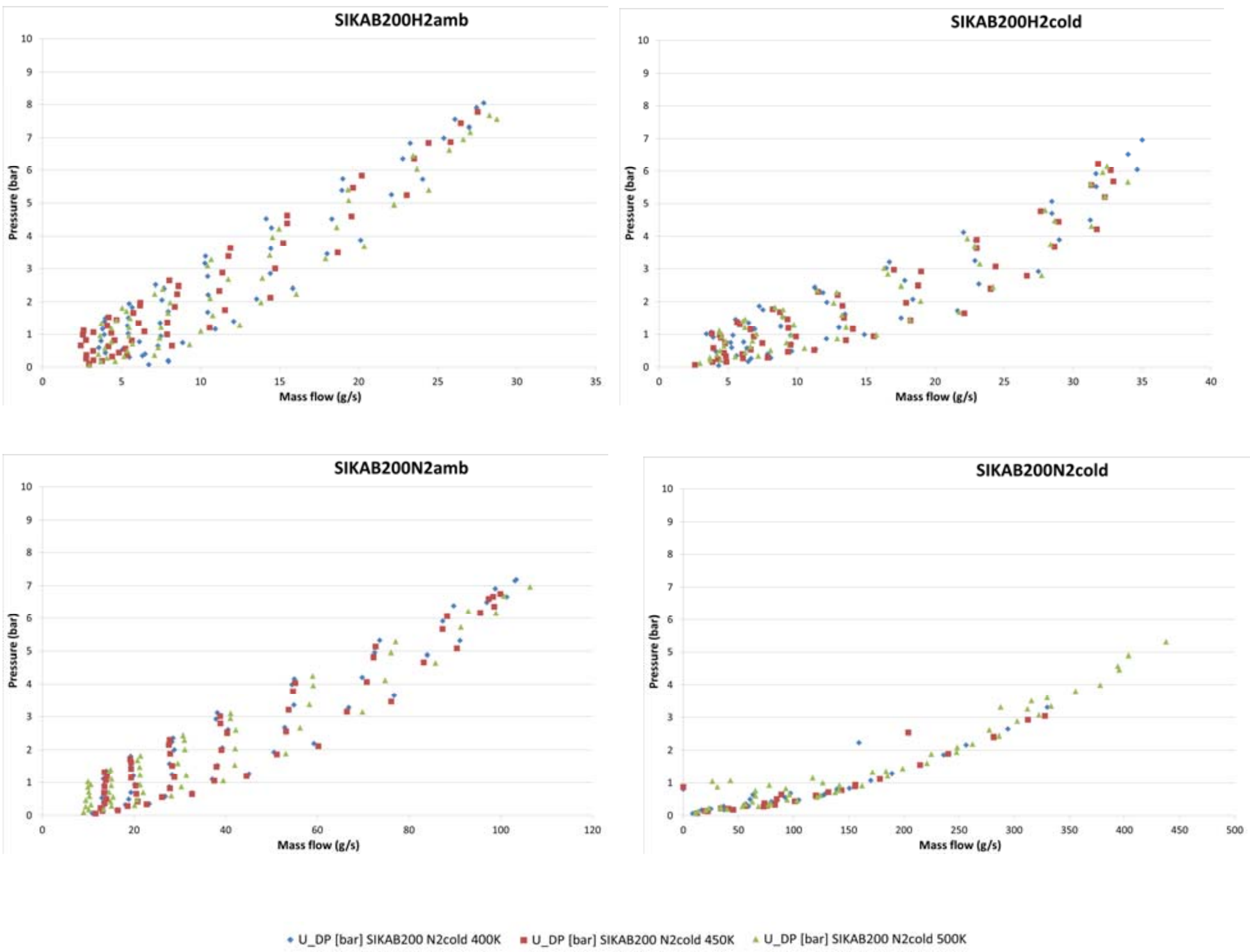

Figure 6: Experimental results SIKAB200: pressure drop function of the mass low

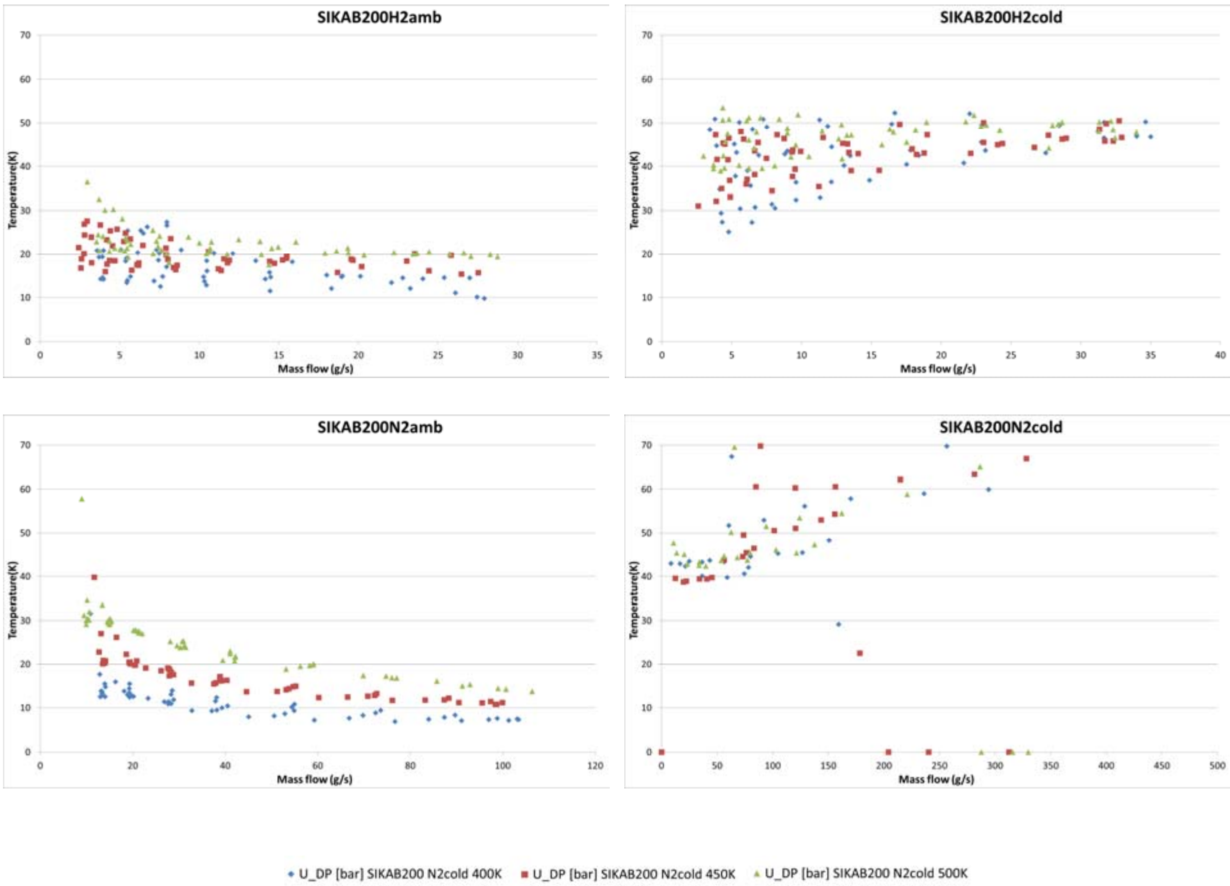

Figure 7: Experimental results SIKAB200: temperature drop function of the mass low

5. Conclusion

The experimental method developed enables the estimation of the permeability and the heat exchange in porous materials for high temperature, high pressure and a wide range of mass flow. Different configurations of fluids, materials and heat loads are also possible. The CFD approach showed the possible modelization of flow and heat exchanges in the porous structure with the conditions specified by the experimental geometry and boundaries. The first experimental results reveal the mass flow as an important parameter for the resulting pressure drop and temperature drop.

Further experimental work has to be made for other samples to analyse the influence of the properties of the porous material such as the geometry of the structure and the porosity. Additional analysis is necessary to estimate the determining parameters for the evaluation of the permeability and the heat transfer. A comparison between experimental results and numerical results will be necessary to analyse the validity of the numerical model. Improvements for the CFD model can already be made such as the application of the thermal equilibrium model.

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