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Numerical modeling of combustion chamber material permeability change

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ABSTRACT

One of the most significant challenges for reaching a Mach number greater than four when using Supersonic combustion ramjet (Scramjet) is the thermal management. To overcome this temperature withstanding issue of materials, the transpiration cooling technique is used. Fuel itself is used as coolant and flows through the walls (porous) of the combustion chamber. Beyond a certain temperature, the fuel is pyrolyzed. This can generate coke particles at the surface and inside the porous material. This progressive formation of coke decreases the material's permeability. Hence, predicting the Darcian permeability evolution of a porous material is very important for better understanding the transpiration cooling technique efficiency. Considering existing experimental data for development and validation, this paper proposes an Artificial Neural Networks (ANN) model for estimating the transient changes of the Darcian permeability of a metallic material during fuel pyrolysis conditions. The ANN architecture with 24 hidden neurons is shown to give the best choice. Good agreement was obtained between numerical and experimental results. The prediction ability of ANN was compared with that of linear regression model. This work is expected to be used by aerospace engineers in order to study the efficiency of the transpiration cooling technique.

1. Introduction

In hypersonic flights (i.e. for flight speeds above Mach 5), the combustion chamber of the engine is subjected to high thermal load. This can damage the walls of the combustor. The so-called transpiration cooling method can serve for this purpose. It consists of injecting a cooling fluid (the fuel itself) through the combustor walls, which are porous, in order to cool them [1–4]. The coolant (endothermic fuel) can react with the materials. In case of chemical reaction (pyrolysis), the formation of carbon coke (as investigated by [5–10]) inside the porosities of the material can impact the permeability of the porous material (lowering its value) over time [11]. Permeability is a critical relevant property affecting the flow through the porous media; and consequently its cooling and the thermal withstanding of the mechanical structure. Thus, in order to better understand and improve the efficiency of the transpiration cooling technique, it is very important to study the evolution of the permeability of porous materials during fuel pyrolysis in case of blocking by solid coke particles for better improving the related knowledge and its mastering under operating conditions.

The complex phenomenology involved in such aeronautical configuration has been deeply investigated [12–18] and is still a hot topic. Experiments are often developed because of the very high cost of computation. Many authors identify experimentally the main products of hydrocarbons jet-fuels decomposition under various operating conditions of pressure, temperature and residence time [15,19,20]. For example, in the case of n-dodecane pyrolysis, the number of reactions which occur is greater than 1000 [21]. This involves very complicated phenomena (mass and heat transfer with chemistry). The flows in porous materials (permeation process) hardly consider both high pressure and high temperature when experimentally investigated. For example, Langener et al. [2] studied pressure up to 2 MPa for ambient to average temperature conditions (under 800 K) and Kuhn and Hald [1] considered low pressure and high temperature. Microscale is impossible to consider experimentally while numerically, it is still a challenge to reproduce the anisotropic behavior of composite materials which are generally used for hypersonic applications.

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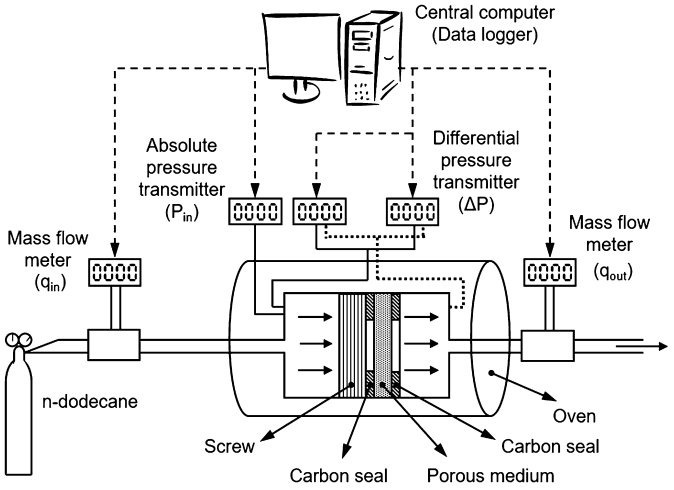

Fig. 1. Schematic of the test bench.

Numerous equations (derived from Brinkman's equation) which relate the permeability of Darcy to the pressure drop (ΔP) across the material sample and to the velocity (or flow rate) have been published [22–25]. Since the phenomena are very complex, space and time dependent and multiphysics related, CFD calculations are still missing to address them properly from the micro to the macro scale. Thus, having a mathematical relation (metamodel) is very interesting practically to save time.

To do so, the approach based on artificial neural networks (ANN) is judge to be promising for simulating the transient changes of the permeability of a porous material. In the last two decades, ANN showed its efficiency in many application fields [26–28]. A model based on ANN approach for simulating the pressure drop of n-dodecane passing through a porous material can be found in a previous study [27]. The key-feature of this approach is that no pre-determined models are needed [29].

The purpose of this study is to predict indirectly the chemical effect of fuel pyrolysis on the permeability of the material which directly controls the cooling efficiency. The databasee, necessary to develop the ANN model, was built using the results coming from an experimental test bench. An artificial neural network has been developed and validated on this database.

2. Material

2.1. Experimental bench

The experimental pyrolysis test bench (Fig. 1) is used to study permeation process under reactive flow conditions [11]. Numerous sensors (3 pressure transducers and 2 Coriolis mass flow meters) are connected to a data logger (16 bits, 48 channels, 0.1 Hz).

A permeation test cell (Fig. 1) containing the porous sample is inserted inside an oven (maximum temperature of 2000 K). This cell is connected to the bottle of the fluid and to the sensors.

In the present study, n-dodecane fuel is used for the experiments because it is known as a good kerosene surrogate. An isotropic stainless steel sample (with a thickness of 3 mm) is chosen because it is well characterized (porosity around 30%, a grain diameter of 14.1 µm, a density of 7850 $\mathrm{kg\,m^{-3}}$ and a pore diameter of 4.1 µm). Further information about the test cell can be found in Fau et al. [11].

2.2. Experimental test methodology/condition

In this work, three different experimental tests have been done for thermal plateaus at 725 K, 765 K and 810 K. Experimental tests are carried out with constant mass flow rate (q_{in}) and given downstream pressure (P_{out}). The measured inlet pressure (P_{in}) increases due to the formation of coke inside the porosity of the porous material. Thus, the pressure drop (ΔP) increases as a function of the test time (t).

The permeabilities of Darcy (K_D) and Forchheimer (K_F) are calculated thanks to the pressure drop and to the flow rate measured as a function of time, using the Darcy–Forchheimer's equation (derived from Brinkman's equation) [25,30,31]:

$$\frac{\Delta P}{L} = \mu \times \frac{V}{K_D} + \rho \times \frac{V^2}{K_F} \tag{1}$$

where $\Delta P = P_{in} - P_{out}$ is the pressure drop through the porous medium, P_{in} is the inlet fluid pressure, P_{out} is the outlet fluid pressure, L is the sample thickness, K_D and K_F are the Darcy's and Forchheimer's permeabilities. The dynamic viscosity (μ), the fluid density (ρ) and the fluid velocity (V) are calculated at the mean value of the inlet and the outlet pressures as defined in ISO 4022 norm. The pressure drop (ΔP) is determined experimentally. The fluid velocity (V) is calculated as follows (Eq. (2)), based on experimental measures of the inlet mass flow meter (q_{in}) and the cross sectional area of the porous material (A).

$$V = \frac{q_{in}}{\rho \times A} \tag{2}$$

The pressure drop through the porous media (left-hand side of Eq. (1)) is proportional to the velocity for low flow rates (Darcian flows) and to its square at higher flow rates (Forchheimer's flow). The Brinkman's equation [23,32] reverts to Eq. (1) for flow in porous media since the Stokes term ($\nabla(\mu \nabla V)$, which represents the viscous effect of very low Reynolds number flow, is normally negligible [32,33]. In Eq. (1), for high fluid flow velocity, the square of the velocity causes the Forchheimer term to be higher than the Darcian one, while for flow speed lower than 1 $\mathrm{m\,s^{-1}}$, the Forchheimer term becomes negligible. More details on the fundamentals of Brinkman's equation can be found in Valdes-Parada et al. [23].

2.3. Experimental results

Before the fuel starts to pyrolyze (for $T \leq 710$ K), the calculated value of the Darcy's permeability (K_D) of the material remains constant ($K_D = 1.96 \times 10^{-13}$ $\mathrm{m^2}$). This value is in complete agreement with the value found at ambient temperature with non reactive fluid (Nitrogen). For experimental results obtained for $T = 725$ K, as shown in Fig. 2 for example, the measured permeability of Darcy (K_D) varies as a function of the pressure drop, of the experimental time (t) and of the measured fuel mass flow rate (q_{in}). These four parameters (t, ΔP, q_{in} and T) have a great influence on the Darcy's permeability. In this study, all the tests are performed with a given mass flow rate (from 0.033 $\mathrm{g\,s^{-1}}$ to 0.1 $\mathrm{g\,s^{-1}}$). Since the mas flow rate is low, no Forchheimer's term can be estimated. Further details on the experimental results can be found in previous work [11].

3. Development of ANN models

3.1. Construction of the database

Pyrolysis is a nonlinear transformation process of mass and energy with strong coupling between flow, heat and mass transfers and reaction [34]. Numerous experimental studies have been done on the pyrolysis of hydrocarbon fuel [21,35,36]. The influence of various parameters on the pyrolysis of hydrocarbons through experiments have been investigated, among which: the pressure