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Injection of polyurethane foaming on a porous medium

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Résumé :

Les mousses de polyuréthane (PU) sont largement utilisées dans la construction, l'industrie automobile, les appareils électroménagers et d'autres domaines. Leur faible poids et leurs excellentes propriétés d'isolation mécanique et thermique résultent de leur structure interne. Elles sont parfois associées à d'autres composants pour obtenir de nouveaux composites de polyuréthane. Les structures en mousse de polyuréthane avec des tissus de renforcement sont fabriquées par des procédés de moulage par injection-réaction (RIM).

Notre étude porte sur le développement de modèles pour la simulation du processus de moussage dans une cavité fermée avec un milieu poreux positionné sur l'une des parois. L'objectif principal est d'étudier l'interaction mousse/milieu poreux en injection afin d'établir un modèle d'écoulement de mousse polymère en milieu poreux.

Des simulations numériques sont réalisées à l'aide du modèle de Stokes-Brinkman dans lequel un tenseur de perméabilité caractérise le milieu poreux. Le modèle de cinétique de réaction, le modèle de densité et le modèle de viscosité déjà développés dans un précédent travail [5] sont adaptés afin de bien décrire le moussage à l'intérieur d'un milieu poreux.

Les calculs présentés correspondent à une géométrie industrielle sur laquelle des expériences ont été réalisées [6]. Il s'agit d'une plaque rectangulaire injectée par son centre. Le matériau poreux considéré est un feutre constitué de fibres de polyester (PET). Par ce type de calcul, on peut donner une évaluation de la profondeur de pénétration dans le milieu fibreux.

Mots clefs : mousse polyuréthane, feutre, injection réactive, simulation

Abstract:

Polyurethane (PU) foams are widely used in construction, automotive industry, household appliances and other fields. Their low weight and excellent mechanical and thermal insulation properties result from their internal structure. They are sometimes associated to other components to get new polyurethane composites. Structures made from polyurethane foam with reinforcing spacer fabrics are manufactured in reaction injection molding (RIM) processes.

Our study concerns the development of models for the simulation of foaming process in a closed cavity with a porous medium positioned on one of the walls. The main objective is to study the foam/porous medium interaction in injection to establish a flow model for polymer foam in a porous medium.

Numerical simulations are made using the Stokes-Brinkman model in which a permeability tensor characterizes the porous medium. Reaction kinetic model, density model and viscosity model already developed in a previous work [5] are adapted in order to well describe the foaming inside a porous medium.

The calculations are made on an industrial geometry on which experiments have been carried out [6]. It is a rectangular plate mold injected through its center. The parameters of porous medium correspond to a polyester felt (PET). With these computations, an evaluation of the penetration depth in the felt can be given.

Key words: polyurethane foam, felt, reactive injection, simulation

1 Introduction

Polyurethane foams are classically used due to their variably adjustable densities as well as their ability to produce either rigid or soft complex forms. Soft-elastic polyurethane foams are rather used in the upholstery area for car seats or mattresses, whereas hard foams have mainly been used as thermal insulation. The epoxy resins or thermoset polymers are used to produce composite. For example, they can contain random continuous glass fiber mats [2]. In other applications, a textile structure is added in the mold, and it acts as a porous medium with both large and small pores. Therefore for producing lightweight composites, polyurethane foam can be advantageously reinforced with fabrics or felts. The standard procedure is to inject the reacting polyurethane mixture through a special designed runner system in a closed mold containing the porous medium [1]. In other applications, the expanding foam must impregnate free space between fibers during this RIM-process. In the same way, the creation of sandwich design [3] in which the polyurethane foam allows increasing lightweight. In this context, the adhesion between foam and the surrounding materials is an important issue [4].

Our study devoted to automotive industries consists in associating a polyester felt to a flexible polyurethane foam. The objective is to improve both mechanical and acoustic properties of the foam. In this context, the evaluation of impregnation depth is important as it gives information on the adhesion between the foam part and the felt components.

There are already numerous articles which are focused on modelling the injection-expansion of polyurethane foam in a mold [5, 14, 15]. However, the modelling and simulation of the combined foam expansion and impregnation process is still a challenging task.

2 Modelling the flow motion in porous media

The modelling without porous media has been already presented in a previous paper [5] and we present here the modifications to handle this porous medium. To model the filling of a mold cavity partially filled by a felt, the momentum, energy and reaction kinetics are required. The porous medium can be characterized by its porosity φ_p and permeability K . The stress tensor is assumed to follow a Newtonian law and it has this expression as the foam is compressible:

$$\boldsymbol{\sigma} = -p \mathbf{I} + 2\eta \left(\dot{\boldsymbol{\epsilon}} - \frac{1}{3} \text{tr} \dot{\boldsymbol{\epsilon}} \mathbf{I} \right) \quad (1)$$

$\dot{\boldsymbol{\epsilon}}$ is the rate of strain tensor and $\text{tr} \dot{\boldsymbol{\epsilon}}$ its trace, \mathbf{I} is the identity tensor, p is the pressure and η the viscosity which is a complex function of temperature, gas content and curing reaction.

This simplest approach to deal with porous media is to mix the Stokes equation and the Darcy's law. That gives the Navier-Stokes-Brinkman macroscopic model which has been successfully used in

simulations of flow in porous media. If the inertial term is neglected, the resulting equation will be valid in the whole computational domain:

$$\nabla \cdot \boldsymbol{\sigma} + \frac{\eta}{K} \mathbf{u} + \rho \mathbf{g} = 0 \quad (2)$$

where the viscosity η and the permeability K are space dependent and are defined on the whole computational domain. A large value of K is chosen outside the porous medium to have the ratio η/K less than 10^{-6} . Note that the velocity in equation (2) is the average velocity through the porous medium whereas the fluid velocity inside the porous medium is equal to \mathbf{u}/ϕ_p . Therefore, the mass balance inside the porous medium is modified as follows:

$$\nabla \cdot \mathbf{u} = \frac{\phi_p}{1 - \phi} \frac{d\phi}{dt} \quad (3)$$

where ϕ is the gas content defined as V_g/V .

The equation describing the average temperature T in the porous medium is written as:

$$\widetilde{\rho c} \frac{\partial T}{\partial t} + \phi_p \rho_f c_f \mathbf{u} \cdot \nabla T = \nabla \cdot (\tilde{\lambda} \nabla T) + \phi_p \left[\eta \dot{\tilde{\epsilon}}^2 + \frac{dT_{ad}}{dt} \right] \quad (4)$$

where the heat generated by reaction kinetics is given by the term T_{ad} . In this equation, the temperature represents the thermal equilibrium between the fluid and the porous medium. Therefore, the mean value $\widetilde{\rho c}$ can be deduced from the density ρ and the specific heat c of each component by a linear mixing law [8] as described by this formula:

$$\widetilde{\rho c} = \phi_p \rho_f c_f + (1 - \phi_p) \rho_p c_p \quad (5)$$

where the solid and fluid parts are labelled by the subscript p and f respectively. The equivalent thermal conductivity $\tilde{\lambda}$ is more complicated to express [7]. For foaming flows the Peclet number is usually very low, hence we assume that the heat dispersion effect due to the pores is insignificant. The effective estimation of this parameter can be made by performing numerical computations on a REV. The equivalent conductivity depends on the main flow direction with respect to felt orientation: if the fluid goes through the porous medium, a harmonic mixing law can be used whereas it is a linear law if the flow is parallel to the porous medium. However, if the flow is at rest, it is shown [7] that the linear mixing gives suitable approximation. In our case the thermal regulation spends more time than foaming, we choose a linear law comparable to relation (5) for the thermal conductivity.

Another novelty corresponds to a new treatment of the pressure. Indeed, the bubble size will exceed the maximal size allowed by the porous medium. Therefore, the bubbles are cut through and this leads in the porous medium to lower gas volume fraction, higher polyurethane volume fraction and eventually higher final mass. This modelling allows a relaxation of the pressure as soon as the gas created during foaming exceeds a critical value [6] which is written as follow:

$$\frac{1}{p} \frac{dp}{dt} = -\xi(\dot{\tilde{\epsilon}}, \phi) \quad (6)$$

The relaxation term ξ also depends on a critical strain dependent term $\dot{\tilde{\epsilon}}$. That reflects the fact that the gas bubbles open more easily under the effect of shear in addition of the size of void in the porous medium. This term can be adjusted by comparison with experimental measurement.

The equations are solved in the whole computational domain Ω with a finite element method. More precisely, all subdomains are embedded in a unique Eulerian mesh using the immersed volume method [9]. A mixed finite element formulation in velocity and pressure is used for Brinkman equations [10-11]. Two level-set functions [12] are used to get implicit representation of both foam/air interface and felt domain. The different sub-domains are depicted in Figure 1.

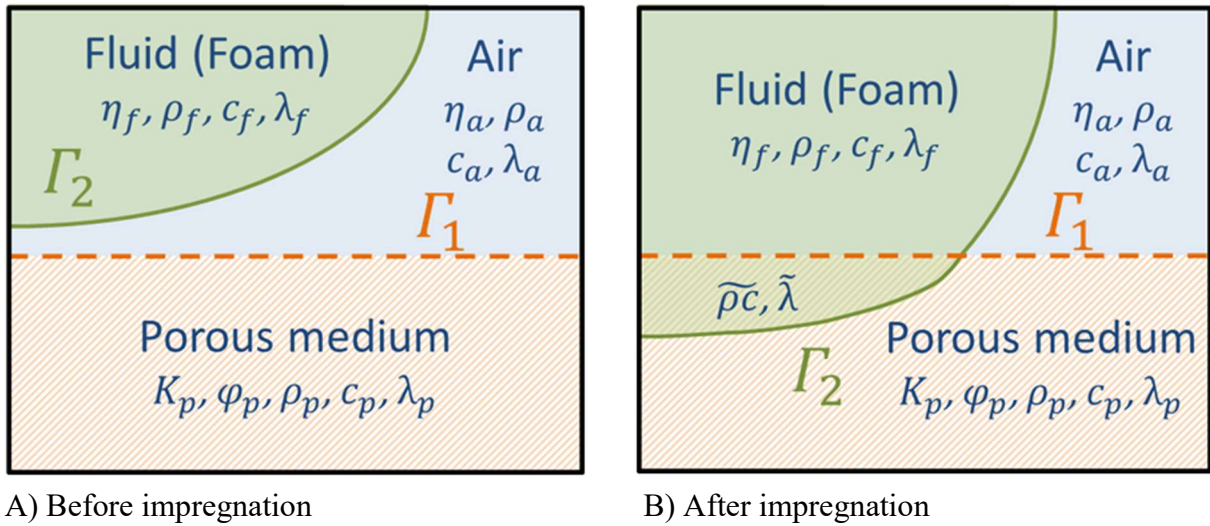


Fig. 1: sketch of Multiphysics approach: notation and definition of different domains (A) before and (B) after percolation in the porous medium.

In this way, one gets a proper definition of the viscosity η , the permeability K , the density ρ , the specific heat c and the thermal conductivity λ as space dependent functions. A global property F is defined using two Heaviside functions H_f and H_s deduced from these level set functions [13]:

$$F = [F_f H_f + F_a(1 - H_f)] (1 - H_p) + \{\varphi_p [F_f H_f + F_a(1 - H_f)] + (1 - \varphi_p) F_p\} H_p \quad (7)$$

where the subscripts f , p and a are respectively associated to foam, porous and air phases. Moreover, as explained in [13], the level-set associated to the fluid/air interface is transported by the velocity solution of the equations (1-3) describing the foam growth.

3 Results

The characteristics of injected polyurethane come from our previous article [5]. As showed in Figure 2, the mold consists of a square metallic frame (size: 900 mm, thickness without the felt: 16 mm) closed by two horizontal plates thermally regulated at 55 °C. The fibrous layer is positioned between the frame and the lower plate. Except for the mass of injected mixture which depends on the absence or presence of the fibrous medium, the injection parameters are identical: the injection rate is equal to 300 g.s⁻¹, the injection temperature is equal to 30°C and the temperature of the upper and lower walls of the mold is equal to 55°C. The variable parameters are the mass of injected mixture, the thickness of the fibrous support as well as its density, its porosity and its permeability.

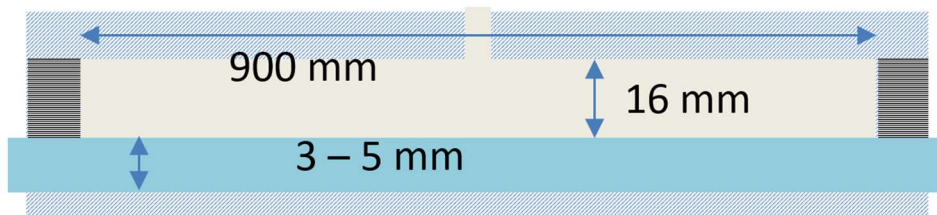


Fig. 2: Vertical cut-plane of mold geometry

To study the mold filling, the case without fibers and an injected mass of 720 g is compared to the case with a low density and thick fibrous layer (5 mm). In this later case, the injected mass is increased to 740 g to fill up the cavity. The characteristic parameters of the felt are $\rho_p = 153.7 \text{ kg.m}^{-3}$, $\varphi_p = 0.902$, $K = 3.7 \cdot 10^{-10} \text{ m}^2$. The mold filling dynamics are computed and shown in Figure 3. The main cavity is filled after 33 s in the presence of the porous layer and after 26 s otherwise. This shows that the presence of the porous layer slows down the filling because the foaming kinetics have not changed. Furthermore, the porous layer was impregnated with a volume of 285 cm³ of mixture (curve in small dotted lines), which corresponds to 28% of its volume.

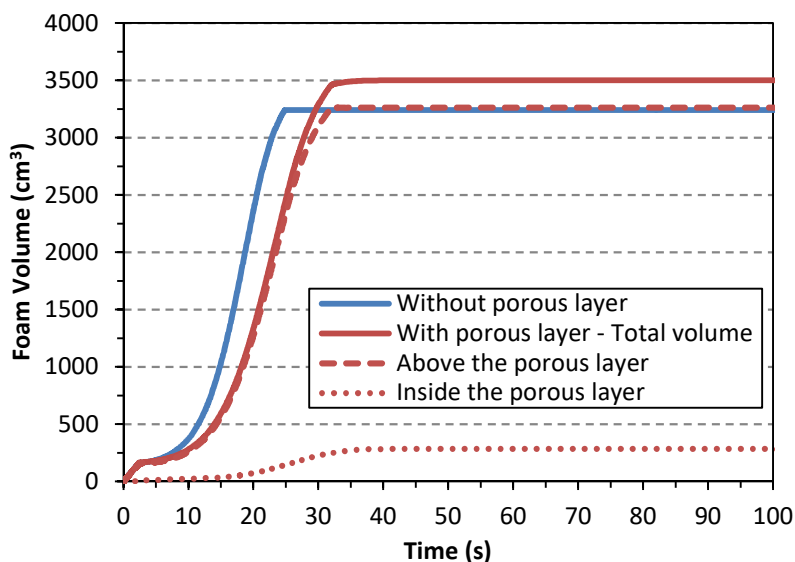


Fig. 3: Evolution of the volume of foam without and with the porous layer

Figures 4 compare the temperature fields in the mold thickness at the end of the foaming during the polymerization ($t = 100 \text{ s}$) in configurations with and without the porous layer. They point out an asymmetry of temperature in the foam thickness.

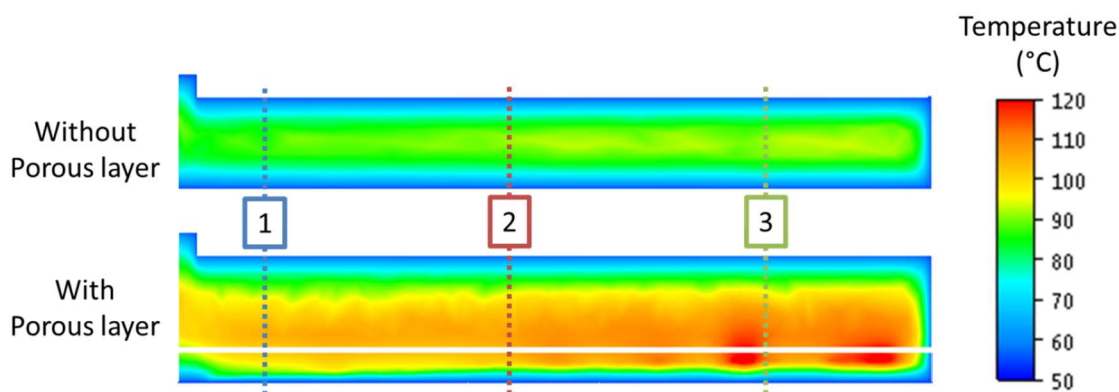


Fig. 4: Temperature field in the mold thickness at $t=100 \text{ s}$ in the cut vertical plane without and with the porous layer

Figure 5 shows the density profile in the vertical cut-plane. Therefore, a foam with an average density of 53 kg.m^{-3} is obtained in the case without porous layer with denser zones near the upper and lower walls of the mold (in particular at position 2) whereas the density is reduced to 48 kg.m^{-3} in the other case due to the mass of mixture having impregnated the porous layer. This figure also gives indications on the impregnation inside the porous medium. Near the injection point, the porous layer is

totally impregnated. The decrease of impregnation depth is observed as the distance from the injection point increases.

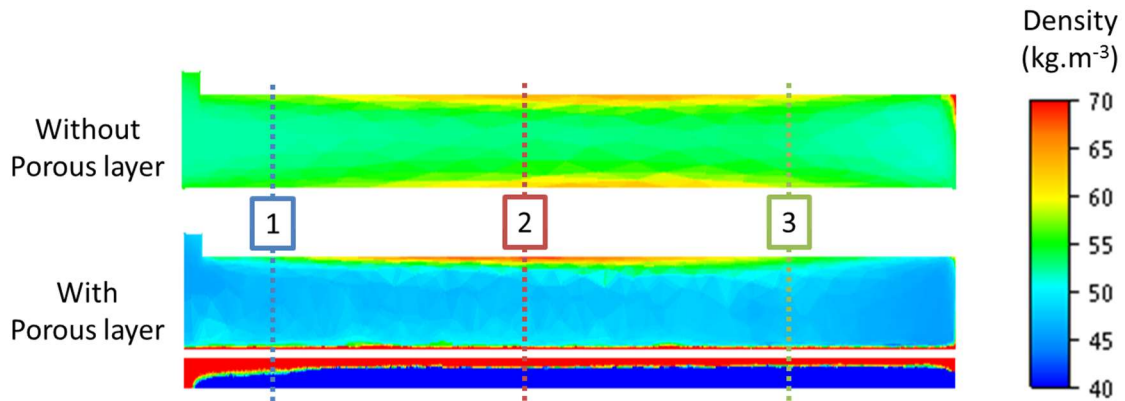


Fig. 5: Density in the mold thickness at $t=100s$ without and with the porous layer

In addition, another computation is made with a felt having thinner thickness (3 mm) and higher density ($\rho_p = 407.7 \text{ kg.m}^{-3}$, $\phi_p = 0.721$, $K = 3.7 \cdot 10^{-11} \text{ m}^2$). This new computation shows a lower decrease in density for a high-density medium [6]. In the same way, the impregnation depth is less important (Figure 6).

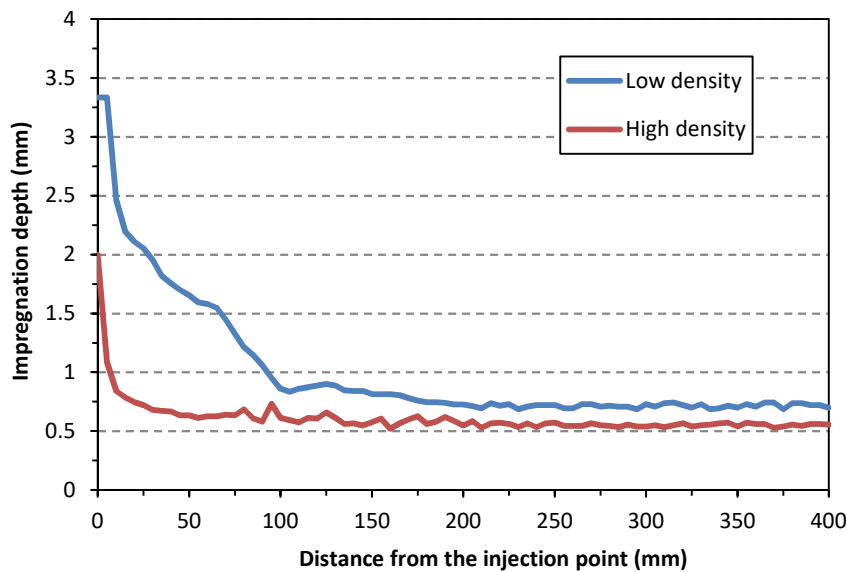


Fig. 6: Impregnation depth along the radial component from injection point for felts having low and high densities.

4 Conclusions

The modelling of polyurethane foaming on a porous layer is studied by using a multiphase approach. This modelling considers a Navier-Stokes-Brinkman flow for the foam in the porous medium. A pressure relaxation model is introduced, and it is possible to account for the decrease in pressure linked to the evacuation of the gas after the opening of the cells due to the porosity of the porous medium. Based on the foaming experiment in a fibrous material [6], a numerical estimate of the value of this coefficient is proposed. A sensitivity study also showed the strong influence of the permeability

of the fibrous medium and the viscosity of the foam on the impregnation distance [6]. The model equations were implemented in REM3D® and the computations on an industrial geometry are presented.

Simulation results showed that the presence of the porous layer increases the time to fill the free cavity. Also, the foam has a lower density, and the size of pores is larger. The temperature field is asymmetric in the mold thickness. The temperature in the foam is indeed higher near the porous medium, and it evolves linearly in the non-impregnated porous medium up to the temperature boundary condition imposed on the lower wall. The impregnation is compared between low density and high-density porous media. The impregnation is more important for low density fibrous media in the first third of the plate on the side of the injection point. This zone may correspond to the initial spreading distance of the injected mixture before the starting time of foaming, which can vary depending on the initial viscosity and the cream time of the foam.

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