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Prediction of acoustic properties of polyurethane foams from the macroscopic numerical simulation of foaming process

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ABSTRACT

This work aims to present a method to predict the acoustic properties of flexible polyurethane foams from the numerical results of a macroscopic simulation of the foaming process. The foaming process simulation is carried out using a meshless method and a set of models taking into account the main chemical reactions, the exothermic effect as well as the thermo-rheo-kinetic coupling. To predict the acoustic properties of the foam, a semi-phenomenological model is used to avoid the experimental characterization of the foam microstructure. The distribution of the non-acoustical parameters involved in the Johnson-Champoux-Allard model were determined using the proposed method for a square panel mold. These results are used to calculate the normal-incidence sound absorption coefficient, which is compared to experimental and numerical results presented in the literature. The predicted acoustic behavior of the polyurethane foam is in good agreement with results in previous works.

1. Introduction

The automotive suppliers produce large amounts of sound-proofing parts in flexible polyurethane foam with more and more complex shapes in order to satisfy customer demands. The complexity of the parts may cause several product defects in foaming process such as air entrapment, weld lines, unfilled regions in the mold ...etc. affecting the quality of the final part. Thus, the numerical simulation of the foaming process is important for the overall design process to define suitable injection points and air vents to avoid these defects. Different authors [1–5] addressed these issues. A presentation of the main works dealing with the foaming process simulation can be found in [5].

On the other hand, an important amount of the flexible polyurethane foams used in the automotive industry is intended to improve the comfort inside cars through the absorption of the sound waves. The acoustic performance of foams can be characterized by estimating a set of intrinsic parameters called "non-acoustic" parameters such as porosity, airflow resistivity, tortuosity, viscous and thermal characteristic lengths [6,7]. The measurement of these parameters is often difficult to perform and is time and money consuming. Therefore, the use of valuable models to predict them is very important.

A literature survey shows that the models can be classified in three categories [8]: the empirical methods [10–14], the scaling laws methods [8,9,15] and the numerical methods [16–18].

For the first category, the parameters of the proposed model are identified by fitting experimental measurements. Dunn and Davern [10] proposed an empirical model to predict the normal acoustic impedance of polyurethane foams. For the same material, Gardner et al. [14] presented an empirical model based on the neural networks to predict the sound absorption coefficient and the surface impedance. Moreover, several works [11–13] concerning fibrous materials proposed empirical models to predict the airflow resistivity, the acoustic impedance and the sound absorption.

The scaling laws methods are based on the calculation of the non-acoustic parameters using the microstructural characteristics of the foam. Doutres et al. [8,9] proposed two semi-phenomenological models to predict the acoustic performance of the polyurethane foam. The authors presented two models to calculate the non-acoustic parameters used in the Johnson-Champoux-Allard model by using the strut length, the strut thickness, and the reticulation rate of the foam in the first model [8]; and then the cell size and the reticulation rate in the second model [9]. They found that the first model is highly sensitive to the microstructure characterization. Despite the adopted simplification, the second model provided better results in the estimation of polyurethane foams sound absorption.

The numerical approaches are based on the use of an idealized representative cell and the solving of a set of fluid dynamic

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equations to calculate the needed parameters. Perrot et al. [16] used this method to characterize the acoustic behavior of the polyurethane foam. The unit cell was idealized by a regular truncated octahedron whose geometric parameters were identified using a non-dimensional numerical model and experimental measurements of porosity and permeability. The authors used the finite element method to solve the Stokes, Laplace, and diffusion controlled reaction equations in order to determine the acoustic properties of the foam. The finite element method was also used by Gao et al. [17] to develop a homogenization model for the estimation of the macroscopic acoustic properties of the foam. The authors used a cubic representative volume element to idealize the foam microstructure.

An accurate prediction of the acoustic performance of the polyurethane foam should take in consideration the foaming process conditions during the part and process design. Indeed, these conditions influence significantly the final microstructure of the foam. In this paper, we present a method to estimate the acoustic properties of the foam from the results of the macroscopic numerical simulation of the foaming process. To do so, a thermo-rheo-kinetic model was first developed to simulate the polyurethane foaming process by the Finite Poinset Method (FPM) and then the semi-phenomenological model proposed by Doutres et al. [9] was used to predict the acoustic foam properties. This work, to the best of our knowledge, represents the first attempt to include the foaming process simulation to predict the final acoustic properties of the polyurethane foam.

In this paper, we present first a brief description of the foaming process model developed in a previous work [5] to make this paper self-contained. We present then the acoustic model adopted to predict the foam acoustic performance using the foaming process simulation. The main results concerning the validation of the proposed model for the foaming process simulation and the non-acoustic parameters are presented and discussed. To validate the acoustic results, the sound absorption coefficient was calculated using the numerical results and compared to experimental and numerical results provided in the literature.

2. Simulation of mold filling with polyurethane foams

Describing polyurethane (PU) foams as a pseudo-homogeneous fluid with continuously changing material properties is a common approach when modelling the mold filling processes [1–4]. The PU foam expansion is governed by the evolution of its density obtained by an empirical equation [19] or by considering the contribution of the chemical reactions, involving the temperature and the viscosity evolution [20–22].

2.1. Polyurethane thermo-rheo-kinetic models

The reactions taking place during the PU foaming are complex, but they can be represented by only two global exothermic reactions: the gelling reaction, where polyol and isocyanate react to form highly cross-linked polyurethane; and the blowing reaction where water and isocyanate react to form urea and carbon dioxide.

Both global reactions are governed by chemical kinetics and are supposed to follow a Piloyan law [23]:

$$\frac{dr}{dt} = \frac{1}{\tau_r} r^{m_r} (1-r)^{n_r} \tag{1}$$

where r is the chemical conversion rate of the blowing reaction ($r = \alpha$) or gelling reaction ($r = \beta$), τ_r is the characteristic time of the reaction, m_r and n_r are the exponents of the reaction rate.

The foam is considered as a generalized Newtonian fluid with its viscosity depending on the temperature (T), the chemical conversion rate of the gelling reaction (β) and the porosity of the foam (ϕ):

$$\eta(T,\phi,\beta) = \eta_0 \exp\left[\frac{E_\eta}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \times \exp\left(\frac{k(T)}{\phi}\right)\left(\frac{\beta_{gel}}{\beta_{gel}-\beta}\right)^{a(T)\beta+b(T)} \tag{2}$$

where η_0 is the viscosity at a reference temperature (T_0), R is ideal gas constant, E_η is the activation energy, β_g is the conversion at gel point, $k(T)$, $a(T)$ and $b(T)$ are the temperature-dependent parameters of the model.

2.2. Governing equations

The general governing equations for compressible Newtonian fluid based on the Stokes' hypothesis include mass conservation, momentum conservation, and energy conservation equations respectively:

$$\nabla \cdot \mathbf{v} = \phi\left(\frac{1}{\alpha}\frac{d\alpha}{dt} + \frac{1}{T}\frac{dT}{dt}\right) \tag{3}$$

$$\frac{d(\rho \mathbf{v})}{dt} = -\nabla p + \nabla \cdot \mathbf{s} + \rho \mathbf{g} \tag{4}$$

$$\frac{d(\rho C_p T)}{dt} = \nabla \cdot (\lambda \nabla T) - (\mathbf{s} : \nabla \mathbf{v}) + Q \tag{5}$$

with:

$$\mathbf{s} = \eta(T,\phi,\beta)\left[(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T\right] \tag{6}$$

$$Q = \Delta H_\beta \frac{d\beta}{dt} + \Delta H_\alpha \frac{d\alpha}{dt} \tag{7}$$

where $\mathbf{v}$ is the velocity vector, $\mathbf{g}$ is the gravity acceleration vector, $\mathbf{s}$ is the deviator part of the stress tensor, $\rho = (1-\phi)\rho_{PU} + \phi\rho_{CO_2}$ is the density of the foam, $C_p = (1-\phi)C_{PU} + \phi C_{CO_2}$ is the thermal capacity of the foam, $\lambda = (1-\phi)\lambda_{PU} + \phi\lambda_{CO_2}$ is the thermal conductivity of the foam, ΔH_α is the enthalpy of the reaction of isocyanate with water and ΔH_β is the enthalpy of the gelling reaction.

2.3. Numerical implementation

Since the 1970s with the emergence of SPH (smoothed particle hydrodynamics), the meshless formulations were developed as an alternative to grid-based numerical methods [24]. Later, a set of methods based on this approach have been developed [25] and to avoid the interpolation consistency at the boundary conditions, several solutions have been proposed such as the finite point method (FPM) [26,27].

For a meshless formulation, the fluid domain is discretized by finite number of Lagrangian particles moving with the fluid velocity, and carrying all fluid properties (density, viscosity, velocity and temperature). To calculate these properties, a list of neighbor points is determined for each point at each time step through the definition of a zone of influence. Indeed, a smoothing length h is attached to each particle and used to create an interpolation function using a Moving Least Square approximation.

The set of differential equations defined by conservation Eqs. (3)–(5) with appropriate boundary conditions are solved in the NoGrid-points software, where the chemical kinetics, the foam viscosity and the source terms defined respectively by Eqs. (1), (2) and (7) were implemented. A splitting technique is used to solve this highly coupled and non-linear system.