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Tooling: Tool simulating the
macroscopic properties of PU foams and
compact TPU

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Abstract:

This document elaborates Polito's and VSCHT's contributions on WP3 and describes the details of Tasks 3.4-6. The main goal of Polito was to develop a CFD solver for PU foams. The CFD solver developed through this research work provides a numerical tool for the simulation of polyurethane foam. The problem includes a reacting multi-phase system in which the liquid mixture expands due to the polymerization phenomenon and the presence of different additives. To accomplish Tasks 3.4-6 VSCHT developed the foam conductivity and foam aging tools both of which are described in detail in the following sections.

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1 Part 1: VSCHT's contributions

1.1 Foam conductivity tool

The main goal of this tool is to predict the heat insulation properties of the final PU foams, which are measured using the so-called equivalent conductivity. Good heat insulator must effectively hinder both heat conduction and heat radiation. This is typically achieved by the selection of blowing agent and by the fine-tuning of the foam morphology.

1.1.1 Equivalent conductivity

The prediction of equivalent conductivity is done using the simulation of coupled conductive–radiative heat transfer. The steady-state energy balance in the foam is written as

$$\nabla \cdot (\mathbf{q}_{\text{tot}}) = \nabla \cdot (\mathbf{q}_{\text{con}} + \mathbf{q}_{\text{rad}}) = 0, \quad (1)$$

where \mathbf{q}_{tot} , \mathbf{q}_{con} , \mathbf{q}_{rad} are the total, conductive and radiative heat flux, respectively.

Here, the foam is viewed as a pseudo-homogeneous material, the conductive heat flux is expressed as

$$\mathbf{q}_{\text{con}} = -k_f \nabla T, \quad (2)$$

where T is the temperature and k_f is the effective conductivity of the foam. The description, how to calculate the effective properties will be given below.

The divergence of the radiative heat flux is written as (?)

$$\nabla \cdot \mathbf{q}_{\text{rad}} = \int_0^\infty \kappa_{f\lambda} (4E_{b\lambda} - G_\lambda) d\lambda, \quad (3)$$

where $\kappa_{f\lambda}$ is the absorption coefficient of the foam, $E_{b\lambda}$ is the blackbody emissive power, G_λ is the incident radiation and λ is the wavelength.

We opted to use the so-called P_1 -approximation and the stepwise gray box model to deal with the of emissive power and incidence radiation on the wavelength. Thus, eq. (1) is rewritten as

$$k_f \nabla^2 T = \sum_{k=1}^N \kappa_{fk} (4E_{bk} - G_k) \quad (4)$$

subjected to boundary conditions

$$T|_{x=0} = T_0, \quad (5)$$

$$T|_{x=L} = T_L, \quad (6)$$

where N is the number of spectral boxes and T_0 and T_L are the temperatures of the boundaries.

The incident radiation is calculated from

$$\nabla \cdot \left(\frac{1}{\beta_{fk}^{\text{tr}}} \nabla G_k \right) = -3\kappa_{fk} (4E_{bk} - G_k) \quad \forall k = 1, 2, \dots, N, \quad (7)$$

subjected to boundary conditions

$$\left. \frac{dG}{dx} \right|_{x=0} = -\frac{3}{2} \frac{\epsilon_0}{2 - \epsilon_0} \kappa_{fk} (4E_{bk}|_{x=0} - G_k|_{x=0}), \quad (8)$$

$$\left. \frac{dG}{dx} \right|_{x=L} = \frac{3}{2} \frac{\epsilon_L}{2 - \epsilon_L} \kappa_{fk} (4E_{bk}|_{x=L} - G_k|_{x=L}), \quad (9)$$

where $\sigma_{f\lambda}$ is the scattering coefficient of the foam and ϵ_0 and ϵ_L are the emissivities of the boundaries. The blackbody emissive power is calculated as

$$E_{bk} = [f(\lambda_{k1}, T) - f(\lambda_{k2}, T)] \sigma_B T^4, \quad (10)$$

where σ_B is the Stefan-Boltzmann constant, f is the so-called fraction of blackbody radiation, which can be calculated using a power series (?) and λ_{k1} and λ_{k2} are the upper and lower bounds of the k -th box.

Equations (4) and (7) represent a system of $N + 1$ coupled partial differential equations. Its solution provides the spatial distribution of temperature and incident radiation. Total heat flux can be calculated from

$$q_{\text{tot}} = -k_f \frac{dT}{dx} - \sum_{k=1}^N \frac{1}{3\beta_{fk}^{\text{tr}}} \frac{dG}{dx}. \quad (11)$$

Finally, the equivalent conductivity of the foam is then calculated as

$$k_{\text{eq}} = \frac{q_{\text{tot}} L}{T_L - T_0}. \quad (12)$$

1.1.2 Effective conductivity

The effective conductivity, which is a measure of the ability of the foam to transfer heat by the conduction, can be calculated in two ways in the Foam conductivity tool.

First, it can be estimated using the analytical model. This approach is based on the work of (?) and can be written as

$$k_f = \frac{k_g \varepsilon + k_s (1 - \varepsilon) X}{\varepsilon + (1 - \varepsilon) X}, \quad (13)$$

where ε is the porosity and X is defined as

$$X = (1 - f_s) X_w + f_s X_s, \quad (14)$$

where f_s is the strut content and X_w and X_s are calculated as

$$X_w = \frac{2}{3} \left(1 + \frac{k_g}{2k_s} \right), \quad (15)$$

$$X_s = \frac{1}{3} \left(1 + \frac{4k_g}{k_g + k_s} \right). \quad (16)$$

And second, the effective conductivity can be calculated using the numerical model. Mathematically, this model is very similar to the model presented in Section 1.1.1 but only with conduction heat transfer, the radiative heat transfer is neglected. Thus, the energy balance is written as

$$k_f \nabla^2 T = 0. \quad (17)$$

Equation (17) is solved in the representative sample of the foam, which has morphology similar to the real foam. This computational domain is automatically created using the Foam construction tool from the given foam porosity, average cell size and strut content.

The numerical is able to include the influence of foam morphology in more detail than the analytical model. However, the numerical model is much more demanding on computational time and memory. Thus, it is convenient to perform first simulations with the analytical model and chose the numerical model only if its precision is not adequate.

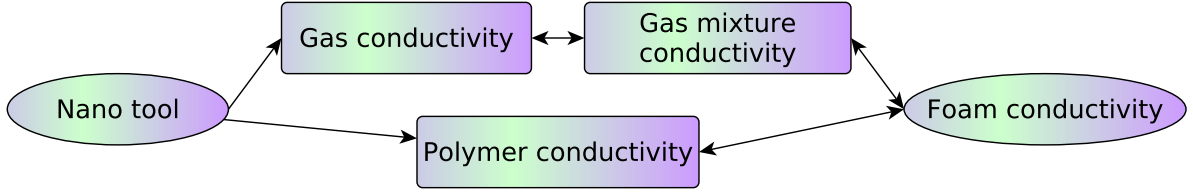


Figure 1: Schematic diagram of the complete multi-scale simulation. The box represents a surrogate model, whereas the detailed model are represented by an ellipse.

1.1.3 Effective radiative properties

The effective radiative properties are calculated under the assumption of independent scattering of struts and walls (??). It is assumed that the foam contains randomly oriented walls, which are modeled as slabs, and randomly oriented struts, which are modeled as long cylinders. The number and cross-sectional area of walls and struts in the unit volume is related to the idealized foam containing dodecahedral cells. Thus, the transport extinction coefficient can be written as

$$\beta_f^{\text{tr}} = (1 - f_s)\beta_w^{\text{tr}} + f_s\beta_s^{\text{tr}}, \quad (18)$$

where β_w^{tr} is calculated as

$$\beta_w^{\text{tr}} = \frac{\rho_f}{2\delta_w\rho_p} \int_0^{\frac{\pi}{2}} [R(\alpha, m) \cos(2\alpha) + 1 - T(\alpha, m)] \sin(2\alpha) d\alpha, \quad (19)$$

and β_s^{tr} is calculated as

$$\beta_s^{\text{tr}} = \frac{4\rho_f}{\pi\delta_s\rho_p} \int_0^{\frac{\pi}{2}} [Q_e(\phi, m) - Q_s(\phi, m) \sin^2 \phi - g_{\text{cyl}}(\phi, m)Q_e(\phi, m) \sin^2 \phi] \cos \phi d\phi. \quad (20)$$

Here ρ_f is the foam density, ρ_p is the polymer density, δ_w is the wall thickness, α is the angle of incidence to the wall, R is the wall reflectance, T is the wall transmittance, ϕ is the angle of incidence to the strut, g_{cyl} is the anisotropy factor and Q_e and Q_s are the extinction and scattering efficiencies of the strut. Reflectance and transmittance can be calculated using the geometrical optics approximation (?). Anisotropy factor and extinction and scattering coefficients can be calculated using the Mie theory (?).

1.1.4 Model coupling

The properties of gas and polymer phase are calculated using nano-scale models developed in MoDeNa project. Specifically, the conductivity of blowing agents and their mixture, the conductivity of polymer and absorption coefficient of the polymer are calculated using various tools. The schematic diagram of the entire multi-scale simulation is shown in Figure 1. The coupling is implemented using the MoDeNa framework (?).

1.1.5 Results and Discussion

The calculated foam equivalent conductivity was compared with experimental data for foam samples prepared in this project (see Figure 2). All information about foam samples is summarized in Table 1, respectively. It can be seen that the experimental and predicted data agree very well regardless of foam density, strut content or cell size.

Table 1: Morphological data of prepared foam samples.

Foam	ρ_f (kg m ⁻³)	δ_c (μ m)	f_s	y_{CO_2}	y_{CyP}
1-1	35.4	510	0.63	0.18	0.82
1-3	49.3	430	0.72	0.27	0.73
1-5	71.4	340	0.85	0.45	0.55
6-6	37.2	380	0.62	1.00	0.00
6-7	56.0	402	0.75	1.00	0.00
7-2	37.9	899	0.72	0.00	1.00
9-6	55.9	619	0.80	0.00	1.00
10-3	39.8	345	0.82	0.50	0.50
10-6	66.1	460	0.68	0.50	0.50

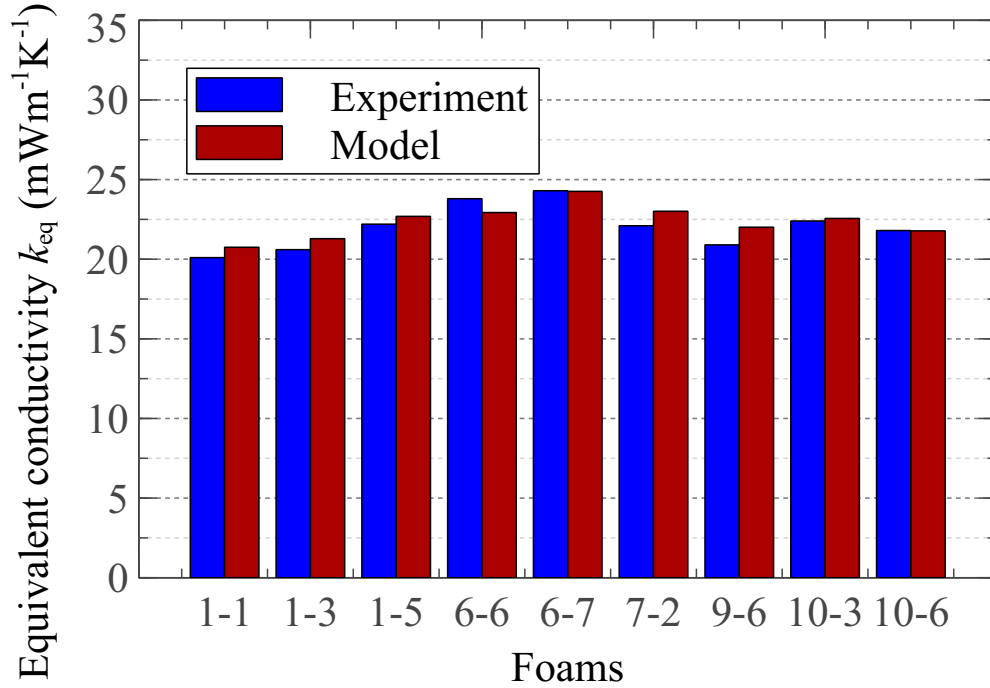


Figure 2: Comparison of measured and calculated equivalent conductivity of prepared foam samples.

Figure 3 shows the dependence of equivalent conductivity and radiative contribution to total heat flux in PU foams on porosity and cell size. For all cell sizes one can find the optimum porosity, at which the equivalent conductivity is minimal. This is caused by the competition between the conductive and radiative heat transfer. The conductive heat flux decreases with increasing porosity, because the high-conducting polymer is being replaced by low-conducting air. Whereas the radiative heat flux increases with increasing porosity, because the lower solid content leads to less absorption of the thermal radiation.

The smaller cell size in PU foams leads to lower equivalent conductivity. This is in contrast with polystyrene foams, where we could see the opposite trend (??). This can be attributed to the much higher absorption coefficient of the polyurethane.

1.2 Foam aging tool

The process called foam aging leads to spontaneous gradual degradation of heat insulation properties over time. This is caused by the fact that the blowing agents are diffusing out of the foam and the air instead diffuses into the foam. Since the air has generally higher thermal conductivity than the blowing agents, the thermal conductivity of the whole foam also increases. This effect can increase the foam equivalent conductivity by more than a third.

1.2.1 Mathematical model

The main barriers against the transfer of gases in and out of the foam are the polymer walls. Thus, the mathematical model is based on the assumption that the foam consists of a series of consecutive parallel walls (?). The polymer walls are further discretized into smaller elements, so that we can capture the evolution of concentration profile even within individual walls. The molar flux between two neighbouring elements is derived from Fick's law as

$$j_i = -D \frac{c_{i+1} - c_i}{\delta}, \quad (21)$$

where D is the diffusion coefficient, c_{i-1} is the concentration in the left element and δ is the thickness of the element perpendicular to the mass transfer.

The molar balance of the i -th element is then written as

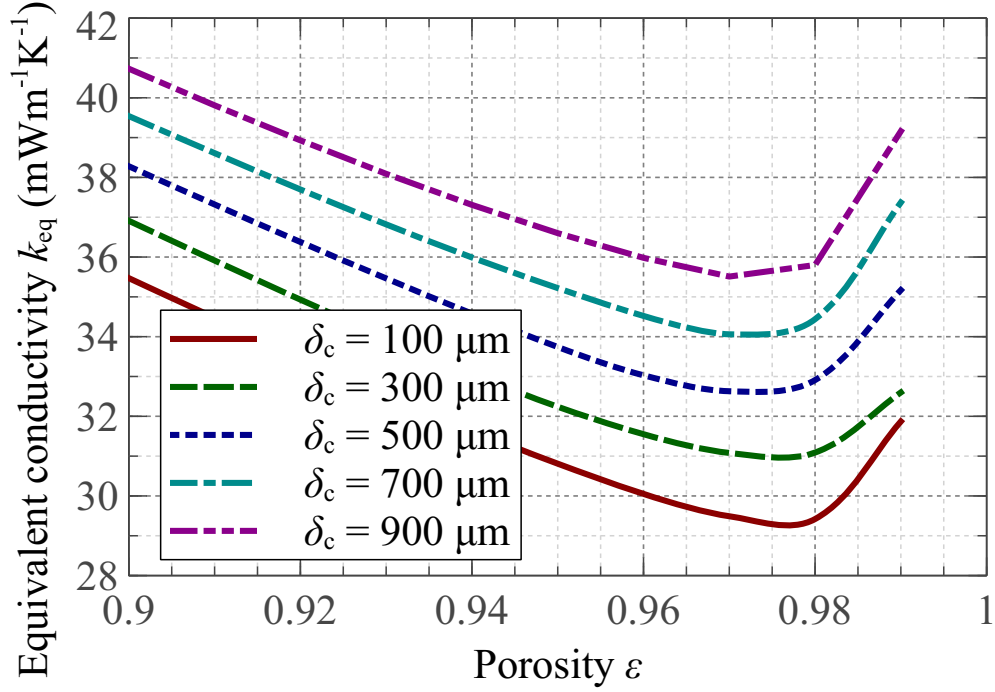
$$V_i \frac{\partial c_i}{\partial t} = A_i (j_i - j_{i-1}). \quad (22)$$

The sorption equilibrium is assumed at the gas–solid interface, which can be written according to the Henry's law as

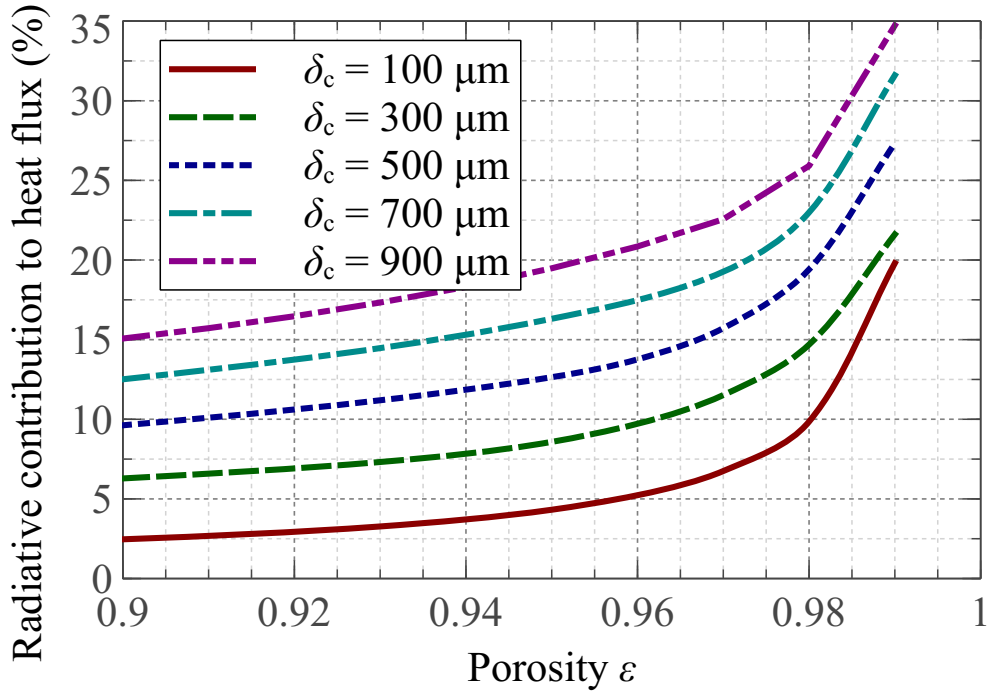
$$c_i = S_i p_i \quad (23)$$

where S_i is the solubility and p_i is the partial pressure. Moreover, the continuity of the mass flux across the interface is enforced.

The solubility and diffusivity of gases in the polymer are calculated using nano-scale models developed in MoDeNa project. The schematic diagram of the entire multi-scale simulation is shown in Figure 4. The coupling is implemented using the MoDeNa framework (?). The morphological parameters, i.e., foam density, average cell size and wall thickness are left as user inputs, thus they must be characterized through image analysis or by other means.



(a)



(b)

Figure 3: The dependence of (a) equivalent conductivity k_{eq} and (b) contribution of radiation q_r/q_t on the porosity and cell size. The strut content was $f_s = 0.8$.

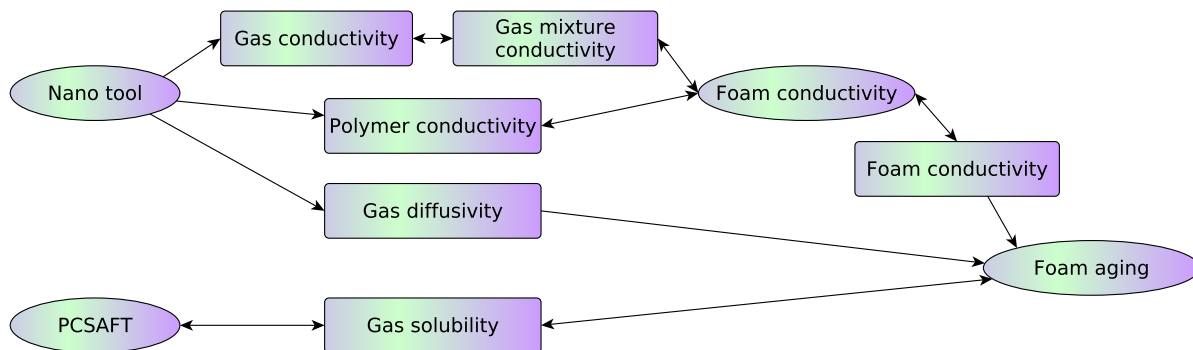


Figure 4: Schematic diagram of the complete multi-scale simulation. The box represents a surrogate model, whereas the detailed model are represented by an ellipse.

1.2.2 Results and Discussion

Figures 5–7 show the comparison of calculated time evolution of foam equivalent conductivity with experimental data. The morphological parameters of individual foams are given in Table 1. The aging test was performed at elevated temperature of 343 K. It can be seen that the equivalent conductivity rapidly increases in the first few days, when the carbon dioxide leaves and the air enters the foam. After approximately 20 days the equivalent conductivity stabilizes. The final conductivity of the water blown foams is higher than the equivalent conductivity of the foams, in which cyclopentane is present. This is caused by the fact that the permeability of the cyclopentane is very low and practically all cyclopentane remains in the foam during the experiment.

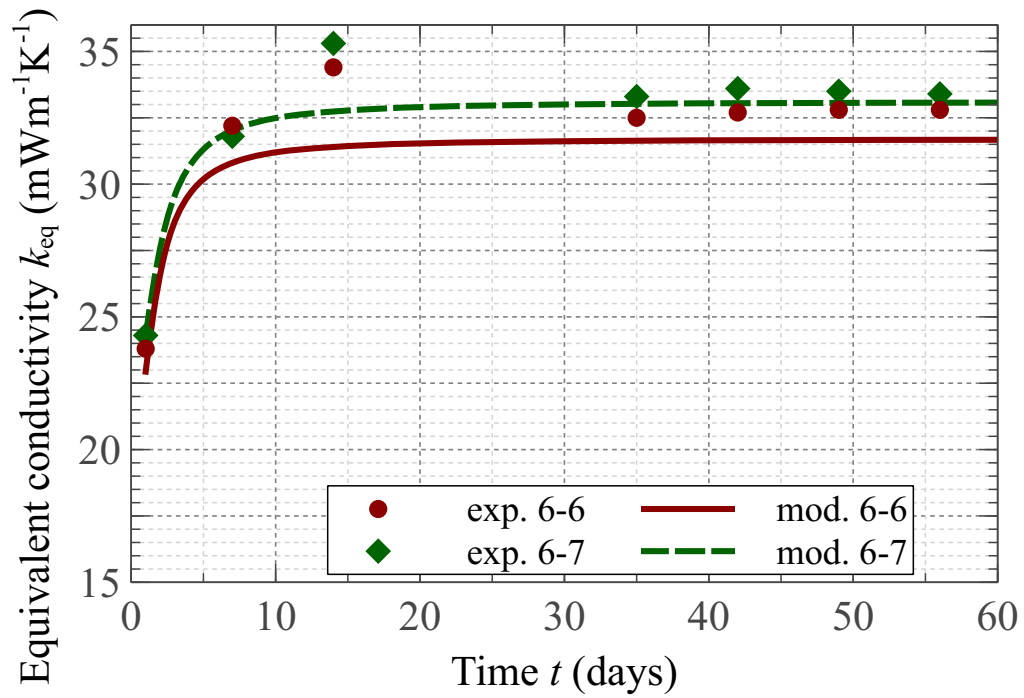


Figure 5: Comparison of calculated evolution of equivalent conductivity with experimental data for water blown foams.

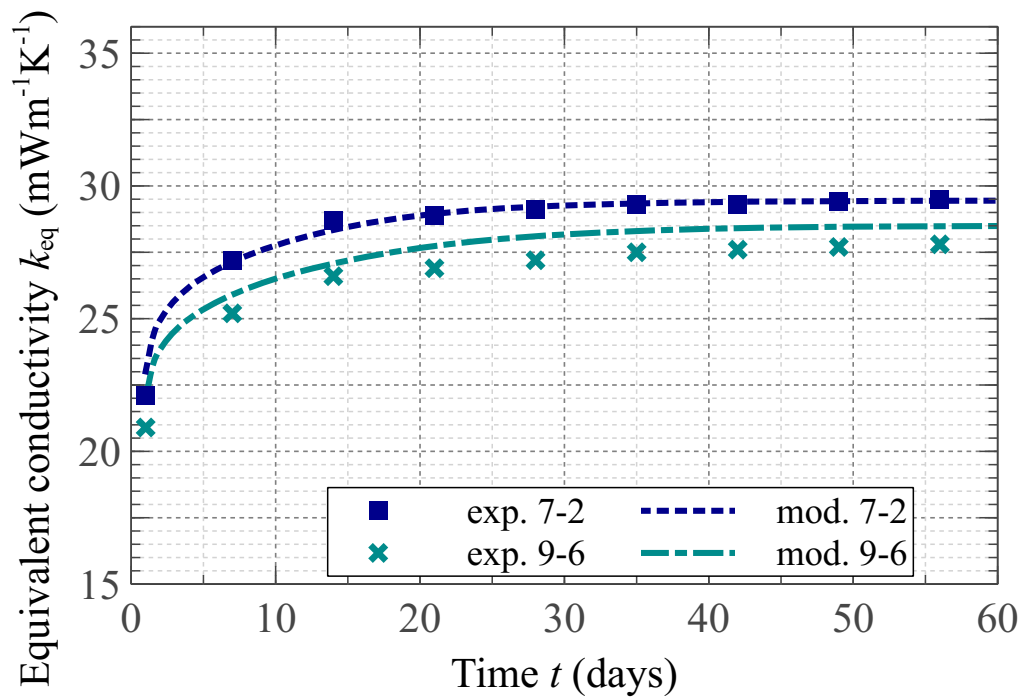


Figure 6: Comparison of calculated evolution of equivalent conductivity with experimental data for cyclopentane blown foams.

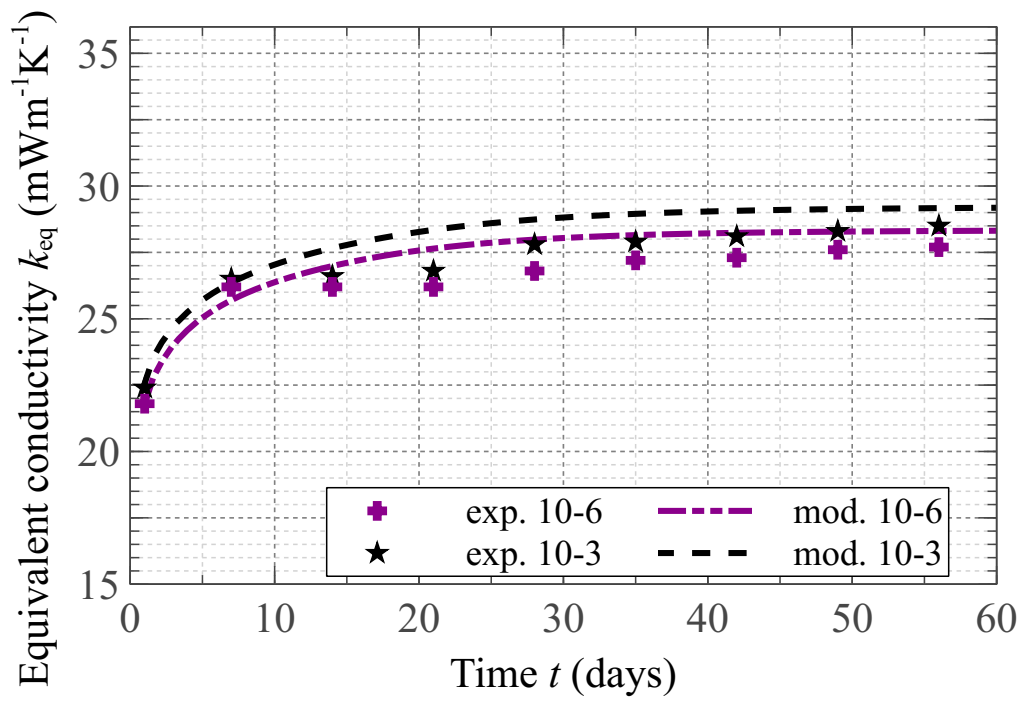


Figure 7: Comparison of calculated evolution of equivalent conductivity with experimental data for foams blown with water and cyclopentane.

2 Part 2: Polito's contributions

D3.4 - Tooling: Tool simulating the macroscopic properties of PU foams and compact TPU

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This document elaborates Polito's contributions on WP3 which is focused on the developing a CFD solver for PU foam. The CFD solver developed through this research work provides a numerical tool for the simulation of polyurethane foam. The problem includes a reacting multi-phase system in which the liquid mixture expands due to the polymerization phenomenon and the presence of different additives. In that, the gas bubbles nuclei within the reacting liquid mixture start to grow owing to the diffusion of gases produced due to the chemical reactions. Further, industrial applications such as mould-filling seek for capturing the foam front face and the evolution of its physical and thermal properties during the foaming process. Thus, the solver shall facilitate the evolution of gas bubbles via a population balance equation, capturing the foam interface using a volume-of-fluid method, and eventually predicts the foam characteristics.

In order to monitor the front face of the expanding PU foam the VOF approach is applied in this work. The focal point is to track the volume fraction of each phase by solving an indicator function. In the case of PU foams, the two phases are the surrounding air as the primary phase, filling the mould initially and displaced by the PU foam which is the secondary phase. Although the PU foam is itself a two-phase system (bubbles with a polymerizing liquid), it has been treated as a pseudo-(single-phase)-fluid. The volume fraction of foam, α_f , is a sharp function that is equal to one at the presence of foam and zero at the presence of air. The first step to assemble the solver is to solve a continuity equation for the volume fraction of the primary phase, α_a :

$$\frac{\partial \alpha_a}{\partial t} + \mathbf{U} \cdot (\nabla \alpha_a) + \nabla \cdot (\mathbf{U}_r \alpha_a (1 - \alpha_a)) = \alpha_a ((1 - \alpha_a) \left(\frac{1}{\rho_f} \frac{D\rho_f}{Dt} - \frac{1}{\rho_a} \frac{D\rho_a}{Dt} \right)) \quad (1)$$

As the two phases share a velocity field (i.e., a single momentum balance equation), \mathbf{U} in Eq. (1) is the mixture velocity and \mathbf{U}_r represents the relative (or compression) velocity. It is worthwhile to note that since the new solver is build upon a compressible solver in OpenFOAM, the right-hand side of Eq. (1) shows

the compressibility effect and for the case of PU foam this effect is interpreted as the density variation.

The fundamental chemical reactions involved in polymerization should also be considered in the model. The gelling (the reaction between isocyanate and polyol) and blowing (the reaction between isocyanate and water) reactions are evaluated by monitoring the conversions of hydroxyl (X_{OH}) and water (X_{W}) in the foam phase. The following general equation form is implemented in the solver:

$$\frac{\partial X_i}{\partial t} + (\mathbf{U} - \alpha_a \mathbf{U}_r) \cdot \nabla X_i = S_i, \quad (2)$$

where S_i is the source term for gelling and blowing reactions that reads as:

$$S_i = \begin{cases} A_{\text{OH}} \exp\left(-\frac{E_{\text{OH}}}{RT}\right) C_{\text{OH}}^0 (1 - X_{\text{OH}}) \left(\frac{C_{\text{NCO}}^0}{C_{\text{OH}}^0} - 2 \frac{C_{\text{W}}^0}{C_{\text{OH}}^0} X_{\text{W}} - X_{\text{OH}} \right), & \text{if } i = \text{OH} \\ A_{\text{W}} \exp\left(-\frac{E_{\text{W}}}{RT}\right) (1 - X_{\text{W}}), & \text{if } i = \text{W} \end{cases} \quad (3)$$

In Eq. (3) A_{W} , A_{OH} , E_{W} , and E_{OH} are the pre-exponential factors and activation energies for the gelling and blowing reactions, respectively. The universal gas constant is defined as R , and T is the absolute temperature of the system. The initial concentrations of isocyanate, polyol and water are defined as C_{NCO}^0 , C_{OH}^0 , and C_{W}^0 .

Additionally, the solver should address the presence of blowing agents, as the gases created by them is the main cause of bubble growth. For this purpose the general mass balance for the i^{th} blowing agent in the mixture is accounted for:

$$\frac{\partial w_i}{\partial t} + (\mathbf{U} - \alpha_a \mathbf{U}_r) \cdot \nabla w_i = r_i \frac{M_i}{\rho_{\text{PU}}} + \bar{G}_1^i \frac{P}{RT} \frac{M_i}{\rho_{\text{PU}}}, \quad (4)$$

where w_i is the mass fraction of the i^{th} blowing agent and where r_i is defined as:

$$r_i = \begin{cases} C_{\text{W}}^0 \frac{DX_{\text{W}}}{Dt}, & \text{if } i = \text{CO}_2, \\ 0, & \text{if } i \neq \text{CO}_2 \end{cases} \quad (5)$$

The molecular mass of i^{th} blowing agent is M_i , and the symbol \bar{G}_1^i represents the moment of order one of the growth rate due to i^{th} blowing agent.

The evolution of the BSD within the foam is described by using a PBE:

$$\frac{\partial n(\mathbf{v})}{\partial t} + \nabla \cdot (n(\mathbf{v}) \mathbf{U}) + \frac{\partial}{\partial \mathbf{v}} [n(\mathbf{v}) G(\mathbf{v})] = \frac{1}{2} \int_0^{\mathbf{v}} h(\mathbf{v}', \mathbf{v} - \mathbf{v}') n(\mathbf{v}') n(\mathbf{v} - \mathbf{v}') d\mathbf{v}' - \int_0^{\infty} h(\mathbf{v}, \mathbf{v}') n(\mathbf{v}) n(\mathbf{v}') d\mathbf{v}'. \quad (6)$$

The number of bubbles (or cells) of the foam with volume between the range of \mathbf{v} and $\mathbf{v} + d\mathbf{v}$ per unit volume of the liquid mixture undergoing polymerization

and constituting the foam is represented by $n(v)$. It is important to stress that the definition of $n(v)$ is done with respect to the volume of the liquid mixture of the foam and not the overall volume of the foam. The other two important terms in Eq. (6) that should be discussed are $G(v)$ and $h(v, v')$. The former expresses the bubble growth rate, while the latter shows the frequency at which the bubbles of volume v and v' coalesce. Following a standard procedure for the solution of the PBE inside CFD, we transform the problem into a set of transport equations for the moments of BSD by applying the generic definition of moment of order k written as:

$$m_k = \int_0^\infty n(v) v^k dv. \quad (7)$$

The merit of this transformation lies on the time efficiency of the numerical method, as typically a small number of moments (i.e. four or six) are necessary. Furthermore, introducing this definition assigns physical meaning for the moments of different order. For instance, the moment of order zero denotes the total number of bubbles per unit volume of the liquid, whereas the first-order moment corresponds to the total bubble volume per unit volume of the liquid. Based on this definition the volume fraction of gas in the PU foam (or void fraction) is defined as: $m_1/(1 + m_1)$, and the mean bubble diameter can be calculated as:

$$d_b = \left(\frac{m_1}{m_0} \frac{6}{\pi} \right)^{1/3} \quad (8)$$

Finally, the general bounded form of the transport equation for the moment of order k within the PU foam phase is as follow:

$$\frac{\partial m_k}{\partial t} + (\mathbf{U} - \alpha_a \mathbf{U}_r) \cdot \nabla m_k = k \sum_{i=1}^z \overline{G}_k^i + \overline{S}_k, \quad (9)$$

with k ranging from 0 to $2N - 1$ and with the number of quadrature node, N , taken equal to two in this work. In order to account for the available number of blowing agents, z in Eq. (9) is the number of blowing agents, and \overline{G}_k^i is the source term for the moment of order k corresponding to the growth rate for the i^{th} blowing agent. The second term on the right hand of Eq. (9), \overline{S}_k , is instead the bubbles coalescence source term for the moment of order k . QMOM is applied to approximate the growth and coalescence source terms:

$$\overline{G}_k^i \approx \sum_{\alpha=1}^N \omega_\alpha G^i(v_\alpha) v_\alpha^{k-1}, \quad (10)$$

where G^i is the growth rate associated with the i^{th} blowing agent,

$$\overline{S}_k \approx \frac{1}{2} \sum_{\alpha=1}^N \sum_{\beta=1}^N \omega_\alpha \omega_\beta [(v_\alpha + v_\beta)^k - v_\alpha^k - v_\beta^k] h(v_\alpha, v_\beta), \quad (11)$$

where, as already mentioned $N = 2$. Also, the N weights and N nodes of the quadrature approximation are defined by ω_α , ω_β and v_α , v_β and are calculated from the first $2N$ moments m_k with the product-difference or Wheeler algorithms.

Knowledge of m_1 (i.e., the total bubble volume per unit volume of liquid mixture of the PU foam) through the solution of PBE suffices the direct evaluation of the PU foam density:

$$\rho_f = \rho_b \frac{m_1}{1 + m_1} + \rho_{\text{PU}} \frac{1}{1 + m_1}. \quad (12)$$

In Eq. (12) ρ_b and ρ_{PU} are the densities of the gas within the bubbles and of the liquid mixture, respectively.

The temperature rise inside the foam is calculated using the following equation:

$$\begin{aligned} \frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{U}T) + (\mathbf{U} - \mathbf{U}_r) \cdot \nabla T - \nabla^2 (\bar{\alpha}T) = \\ \frac{\alpha_f}{\rho_{\text{PU}} c_f} \left[-\Delta H_{\text{W}} C_{\text{W}}^0 \frac{DX_{\text{W}}}{Dt} - \Delta H_{\text{OH}} C_{\text{OH}}^0 \frac{DX_{\text{OH}}}{Dt} + \Lambda \sum_{i=1}^z \frac{Dw_i}{Dt} \right], \end{aligned} \quad (13)$$

$\bar{\alpha}$ is the thermal diffusivity of the PU foam, whereas, ΔH_{W} and ΔH_{OH} indicate the heats of the blowing and gelling reactions, and finally c_f is the specific heat capacity of the PU foam.

The solver is also equipped with two rheological models: a simple Newtonian model and a more advanced non-Newtonian model. In summary, the Newtonian formulation relates the foam viscosity to the foam temperature, T , and conversion of isocyanate, X_{NCO} , using Castro-Macosko model:

$$\mu_f(T, X_{\text{NCO}}) = \mu_\infty \exp\left(\frac{E_\mu}{RT}\right) \times \left(\frac{X_{\text{NCO,gel}}}{X_{\text{NCO,gel}} - X_{\text{NCO}}}\right)^{(a+X_{\text{NCO}}+cX_{\text{NCO}}^2)}, \quad (14)$$

where $\mu_\infty = 10.3 \times 10^{-8}$ (Pa s), $\frac{E_\mu}{R} = 4970$ K⁻¹, $X_{\text{NCO,gel}} = 0.65$, $a = 1.5$, $b = 1$, and $c = 0$ are the model constants and the conversion of isocyanate is computed using the following expression:

$$X_{\text{NCO}} = \frac{C_{\text{NCO}}^0 - (C_{\text{NCO}}^0 - X_{\text{OH}} \cdot C_{\text{OH}}^0 - 2X_{\text{W}} \cdot C_{\text{W}}^0)}{C_{\text{NCO}}^0}, \quad (15)$$

The non-Newtonian model is instead based on the Bird-Carreau theory resulting in the following implementation:

$$\mu_f(T, X_{\text{OH}}, \dot{\gamma}) = A_{\text{OH}} \exp\left(\frac{E_{\text{OH}}}{RT}\right) \times \left(\mu_\infty + (\mu_0 - \mu_\infty) (1 + (\dot{\gamma}\bar{\Lambda})^\zeta)^{\frac{n-1}{\zeta}}\right), \quad (16)$$

In Eq. (16) μ_0 and μ_∞ define the values of foam viscosity under the minimum and maximum shear rates, and have a functional form identical to Eq. (14). The constants utilized in this work are: $\bar{\Lambda} = 11.35$, $\zeta = 2.0$, and $n = 0.2$.