Modeling of Fluid Flow and Heat Transfer During a Steam-Thermolysis Process for Recycling Carbon Fiber Reinforced Polymer

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Introduction

Different types of technologies to recycle carbon fiber reinforced polymer (CFRP) waste have been studied. The steam-thermolysis is a process that combines pyrolysis and superheated steam at atmospheric pressure to decompose the organic matrix of the composite. The waste is introduced into a bench-scale reactor heated at high temperatures under nitrogen atmosphere. A humidity generator is coupled in the reactor gas inlets to provide a flux of superheated steam. A 3D model was built using COMSOL Multiphysics Software to better understand velocity and temperature profiles during the steam-thermolysis process within the reactor.

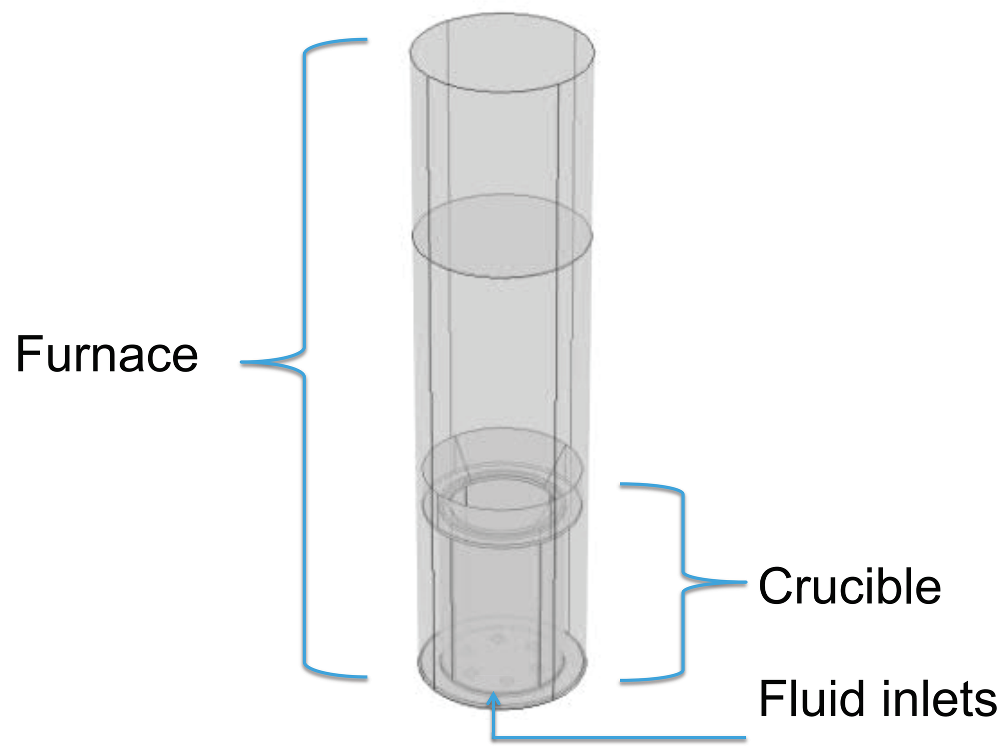


Figure 1. 3D reactor geometry

Computational Methods:

Fluid flow

The hypothesis on the flow regime was justified by calculating Reynolds number with the maximum steam flow rate used during the steam-thermolysis.

$$Re = \frac{\rho \times v \times 2r}{\mu} = 13 < 2000 \quad ^{*}$$ (Régime laminaire)

The Navier-Stokes equations were applied to model the fluid flow within the furnace.

$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = \nabla\cdot\left[-P + \mu(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) - \frac{2}{3}\mu(\nabla\cdot\boldsymbol{u})\right] + F \quad ^{*}$$

$$\nabla\cdot(\rho\boldsymbol{u}) = 0$$ (compressible flow)

Boundary conditions
- Inlet: steam flow rate W_m= 50 – 200 g/h;
- Outlet: P = 1 atm;
- Wall: no slip (u = 0) .

Heat Transfer

A general heat transfer equation including conduction, convection and radiation was used in the model.

$$\rho C_P \boldsymbol{u}\cdot\nabla T = \nabla\cdot(k\nabla T) + Q \quad ^{*}$$

Surface to surface radiation interface was also applied to simulate the radiation effect.

$$J = (1-\varepsilon)G + \varepsilon\sigma T^4 \quad ^{*}$$

Boundary conditions
- Inlet: T_e = 400-500°C;
- Outlet: $-n \cdot (-k\nabla T) = 0$;
- Furnace temperature: $T = T_e$ + 100°C;
- Heat source (Q): Heat released from the reaction.

*ρ: the density of fluid kg m^{-3} ; u: the velocity m s^{-1} ; μ: the dynamic viscosity Pa s; P: pressure Pa; F: the vector of volume forces N m^{-3}; Cp: the specific heat capacity of the fluid kJ $kg^{-1}k^{-1}$; T: temperature K; κ: thermal conductivity of the materials W $m^{-1}K^{-1}$; Q: heat source W m^{-3}

Results

Without composite

The fluid velocity is more sensitive to steam flow rate changes than temperature changes;

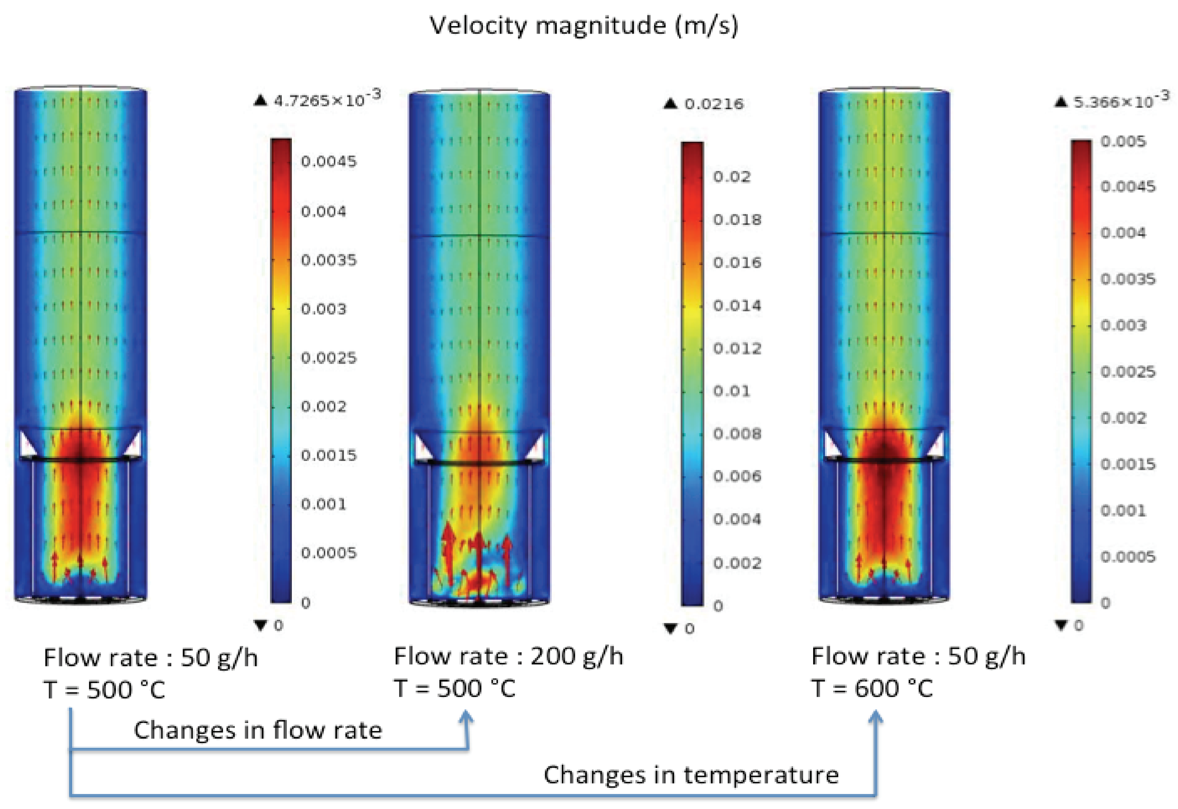
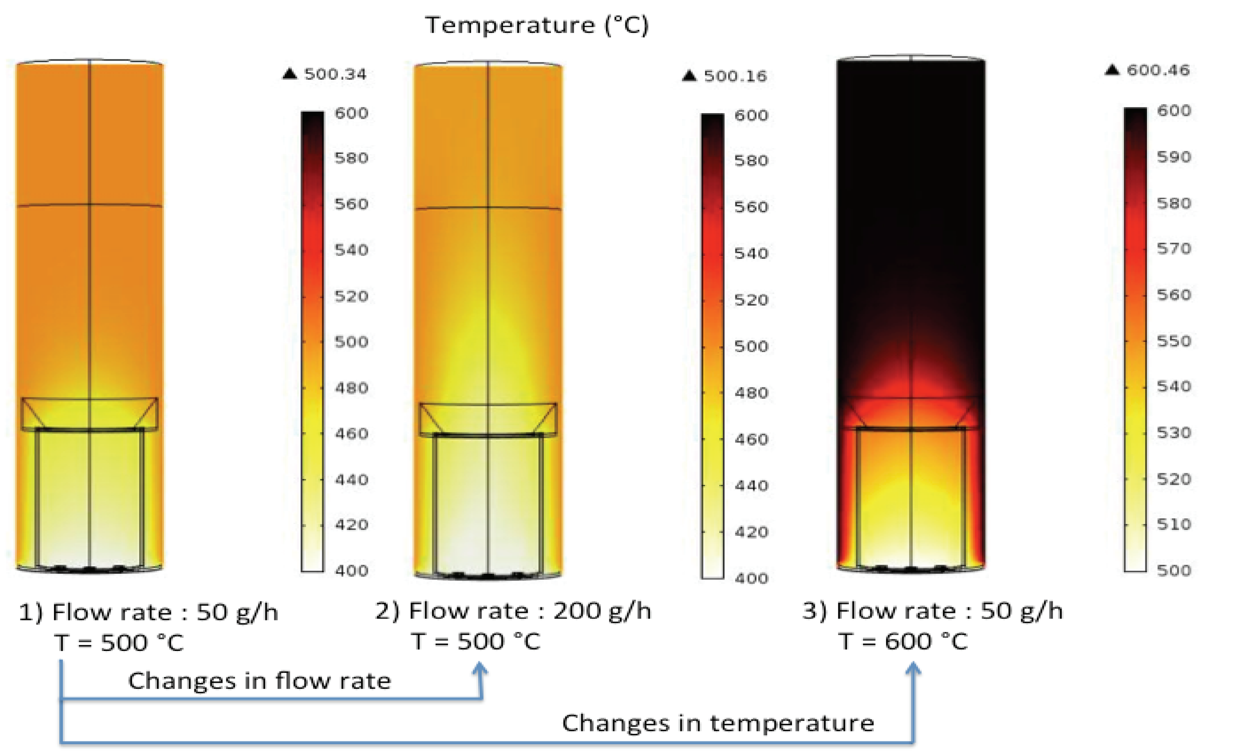


Figure 2. Effects of different parameters on velocity profile

The temperature decreased when the flow rate increases.



	Average Temperature
1)	484 °C
2)	474 °C
3)	583 °C

Figure 3. Effects of different parameters on temperature profile

Composite influence

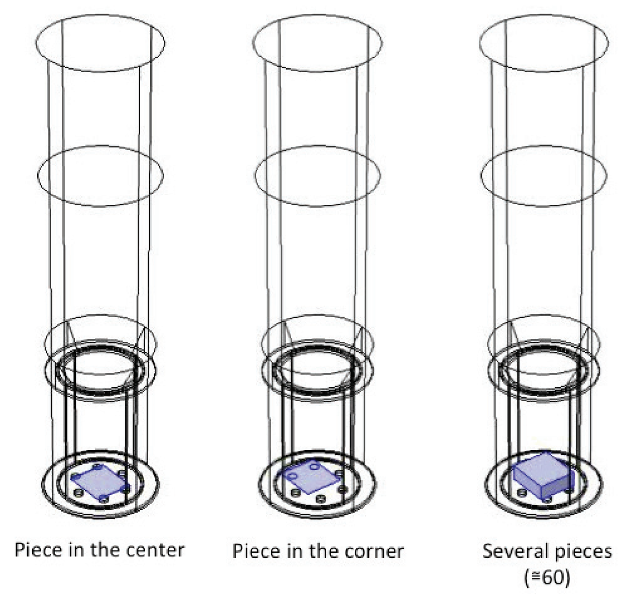


Figure 4. Pieces arrangements

- The introduction of composites produces an increase of the fluid velocity at crucible inlet;
- The environment around the composite becomes colder when the number of composites pieces increases.

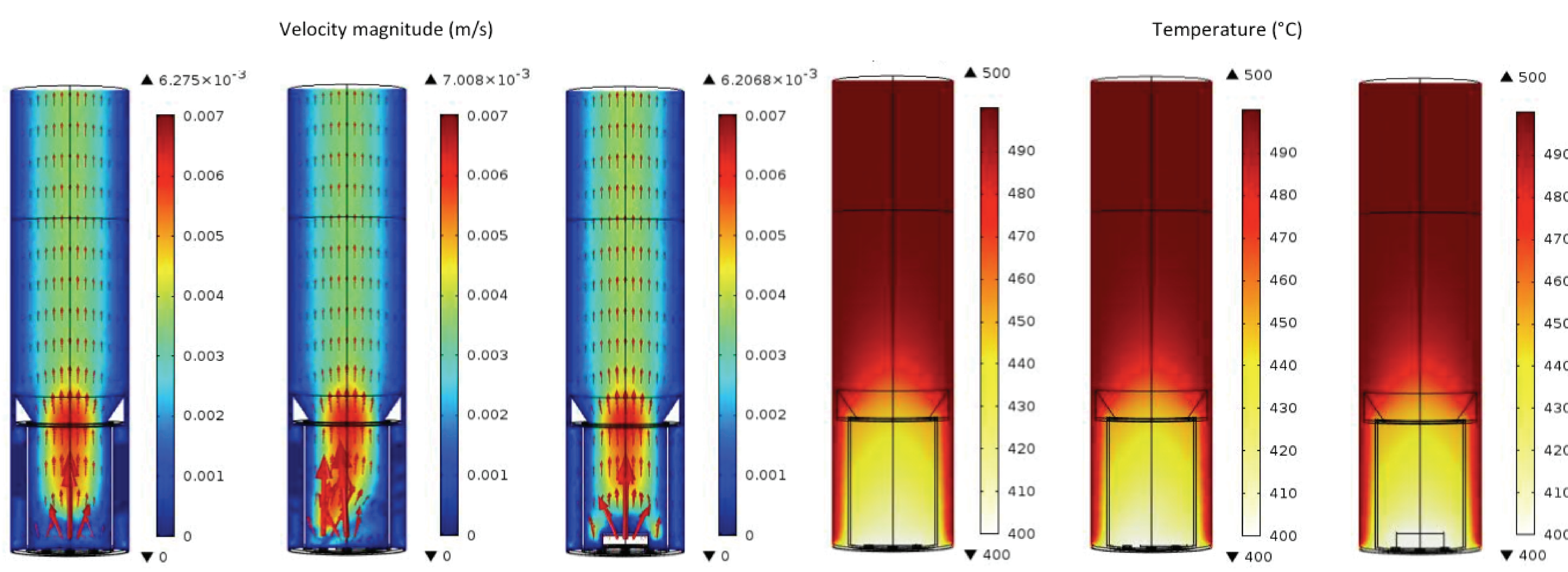


Figure 5. Effects of the introduction of composites

Conclusions

- The 3D COMSOL model is a useful tool for gaining a better insight into temperature and velocity profiles in the furnace during the steam-thermolysis;
- The increase of the steam flow rate and/or the furnace temperature leads a reduction in the residence time within the reactor. Conversely, the flow changes may affect the temperature profile within the crucible;
- The decomposition reaction of the composite polymer resin will be further integrated in the model.

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