SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Solar Fuels and Chemical Commodities

https://doi.org/10.52825/solarpaces.v3i.2359

Published: 18 Nov. 2025

Waste Biomass Fast Pyrolysis in a Drop-Tube Reactor Using Concentrated Solar Power

CIRCULAR FUELS - EU PROJECT

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Abstract. Solar-assisted pyrolysis is a sustainable process for the conversion of biomass into bio-oil using renewable solar-thermal energy with potentially zero carbon footprint. The EU's target of reducing net greenhouse gas emissions to at least 55% by 2030 leads the way to effective measures in limiting carbon emissions for a climate-neutral future. This study focuses on the initial design and development of a drop-tube fast pyrolysis reactor that performs the conversion of waste biomasses into bio-oil at 600°C, by using concentrated solar power. This work is part of the European Union-funded project, Circular Fuels, which focuses on the production of sustainable aviation fuels (SAFs). The numerical CFD simulations were performed using the ANSYS FLUENT 2020 commercial CFD solver for the sizing and design optimization of the experimental solar reactor prototype.

Keywords: Biomass, Fast Pyrolysis, Concentrated Solar Power, Sustainable Aviation Fuel, Tubular Solar Reactor, Computational Fluid Dynamics (CFD)

1. Introduction

The aviation transport industry is one of the most prominent CO_2-producing sectors in the EU, accounting for about 14.4% of the EU transport emissions. To reduce these emissions and to make the EU climate-neutral, the 'Fit for 55' package' effectuated a set of proposals to increase the use of Sustainable Aviation Fuels (SAFs) by aircrafts and to ensure that a minimum of 2% of SAF is available to EU airports in 2025 and eventually 70% of SAF by 2050 which can be partly satisfied with the production of advance biofuels and green hydrogen. The Circular Fuels project [1], funded by the European Union (Horizon Europe) in collaboration with 9 different organizations, aims to produce SAF by using concentrated solar energy for the pyrolysis of biowaste feedstocks through advancements in renewable energy harvesting and technological innovation. This process will convert cheap and abundant waste wood and agricultural residues into renewable bio-oil using solar-assisted fast pyrolysis, eliminating combustion, and valorizing by-products.

Pyrolysis reactors require extensive heat energy for biomass decomposition and conventional external heating systems such as biomass combustors or internal electric heaters are being used but either consume the raw material or high-grade electricity for heating [2]. Therefore, incorporating solar thermal energy in biomass conversion is clearly a sustainable option where an unlimited source of renewable energy is used with a potentially zero carbon footprint. Though a majority of solar pyrolysis reactors operate at high temperatures (above 1000 °C) for the production of syngas [3], the developed low-temperature solar-assisted pyrolysis reactor aims to reach a higher yield of bio-oil from the waste biomass by operating at an optimal reaction temperature of around 400-600 °C [4]. As part of the initial conceptualization and design of an experimental solar drop-tube reactor, numerical CFD simulations were carried out using the commercial ANSYS FLUENT 2020 solver. This paper presents the methodology and the first results of the solar reactor prototype sizing.

2. Reactor concept

The proposed solar pyrolysis reactor is of tubular type that can be operated either as a fixed bed, entrained flow, or fluidized bed as shown in Figure 1. The bio-mass is fed vertically, falling by gravity into the tube, entrained by an inert fluid such as argon. The millimetric biomass particles are suspended in an inert argon gas stream, which creates a dynamic environment that enhances heat/mass transfer and mixing [5]. An external tube diameter of 30 mm was set to match the capacity of the 2m diameter solar concentrator available in the lab. The reactor tube is covered by insulation blocks that prevent heat losses toward surrounding. This insulation block consists of an open-air receiver cavity with a circular orifice of 15 mm diameter and 177 mm² surface area. The solar reactor can operate at a maximum entering power of 1.5 kW, yielding a mean irradiation flux of about 8 MW/m² at the aperture. The irradiation directly heats the reactor tube and the waste biomass particles thereby undergo fast pyrolysis. For an ideal pyrolysis reactor design, it is necessary that the reactor attains homogenous heating and maintains a minimum temperature of 500°C along the heated tube length for effective pyrolysis.

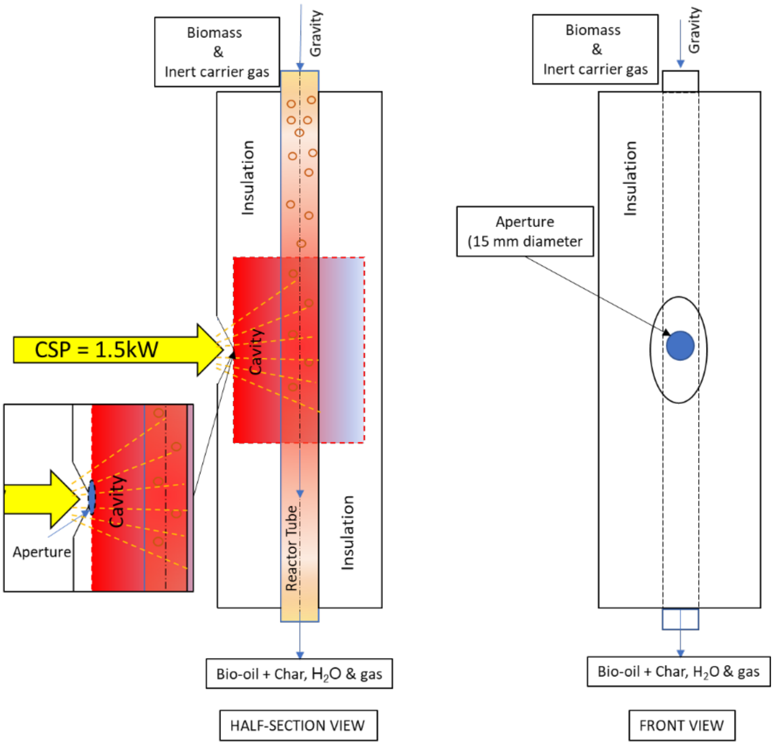

Figure 1. *Illustration of a drop-tube solar pyrolysis reactor*

3. Numerical CFD modelling

The numerical study follows a validation methodology where the initial sizing of the solar receiver cavity was studied as a 2D axisymmetric CFD model with coupled fluid flow and heat transfer (conduction, convection, and radiation). The results of the 2D axisymmetric model were then compared against a 3D CFD model for similar solar input. The 3D model was further used for the optimization of the reactor's thermal performance.

3.1 2D Model

The parametric study of the reactor was first carried out using a simplified 2D axisymmetric geometry as shown in Figure 2a, consisting of a 650 mm long vertical primary mullite tube (23 mm internal diameter, and 30 mm external diameter). The reactor tube is surrounded by thermal insulation, made of Ultra board 1600 – 400 material with a maximum thickness of 67 mm. The material physical properties are provided in Table 1. The center of the insulation body contains a cavity receiver of 100 mm nominal height and 118 mm inner diameter, along with a 0.5 mm height aperture which has a cylindrical surface area of 177 mm², equivalent to the surface area of the 15 mm diameter circular orifice. The insulation body contains a V-shaped solar entry connected with a 120° angle to the 0.5 mm slit where the incident solar radiation enters. No biomass is fed in the reactor for these thermal simulations as the pyrolysis enthalpy is low and will only slightly affect the reactor temperature profile. Inert argon gas is, injected at 0.5 NL/min vertically downward into the tube. The simulation follows a steady-state two-dimensional axisymmetric laminar flow model with conjugate fluid flow and heat transfer, based on energy model and Discrete Ordinates (DO) radiation approach with '16 divisions and 20 pixels' angular discretization. A heat transfer coefficient of 10 W/m².K was set for convection at the external walls. This model notably enabled to study the effect of cavity height (from 100 mm to 300 mm).

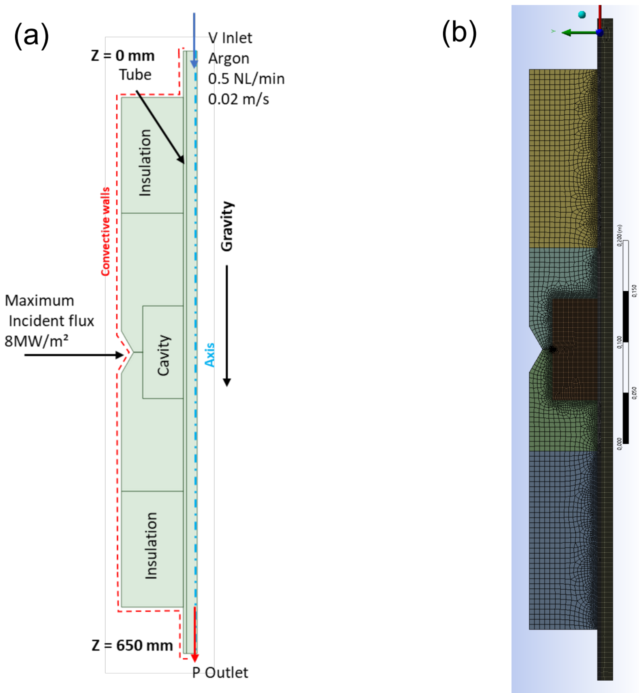

Figure 2. *(a) 2D model setup of the solar reactor, (b) 2D model mesh view*

The mesh sensitivity analysis of the model indicated that for a range of varying element sizes (10 mm to 1 mm), the model with a linear mesh of 1 mm element size for the fluid cell zone and 5mm for the insulation cell zone as shown in Figure 2b, exhibited optimal results accuracy.

Table 1. *Material physical properties considered*

Component	Material	ρ (kg.m^{-3})	c_p (J.kg^{-1}.K^{-1})	λ (W.m^{-1}.K^{-1})	µ (kg.m^{-1}.s^{-1})
Reactor tube	Mullite (EM-60)	2700	900	5	
Insulation	Ultra-board (1600-400)	400	800	0.5 (at 1073.15 K) 0.22 (at 1473.15 K)	
Inert Fluid	Argon at 300 K	1.6228	520.64	0.016	2.13 x 10^{-5}
Solar Cavity	Air at 300 K	1.225	1006.43	0.024	1.79 x 10^{-5}

3.2 3D Model

The 3D model is simulated with two different solar receiver cavity design variants, as shown in Figures 3a (3D model) and 3b (optimised 3D model). The first variant (Figure 3a) consists of a cylindrical solar cavity of 300 mm height and 118 mm diameter, similar to the 2D model. The second variant (Figure 3b) is designed with an optimised cavity shape for the same height, with the aim to improve thermal performance (higher insulation width at the back of the reactor). The insulation body of both the reactor variants consists of a conical extrusion including a circular orifice of 15 mm diameter (surface area ≈ 177 mm²) to let enter the concentrated solar power. The numerical setups and input values for both the 3D models were set identical to that of the 2D model for comparison purposes. The simulation follows a steady-state three-dimensional laminar flow model with coupled fluid flow and heat transfer, based on energy model and Discrete Ordinates (DO) radiation approach with ‘16 divisions and 20 pixels’ angular discretization. A heat transfer coefficient of 10 W/m².K was set for convection heat transfer at the external walls. The 3D model was especially developed to analyse the effect of non-axisymmetric solar input and for design optimization. The mesh sensitivity study revealed that a mesh with 5mm base cells yielded optimal results accuracy.

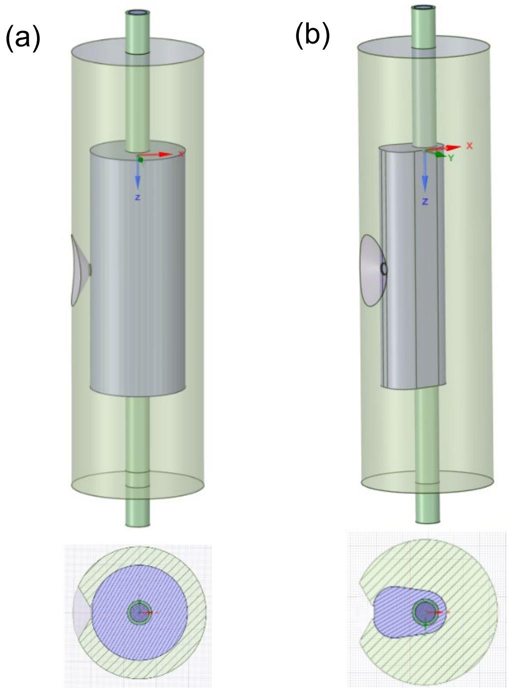

Figure 3. *(a) 3D model of the reactor with the cylindrical cavity, (b) 3D model of the reactor with the optimised cavity*

4. Results & discussion

4.1 2D Model

The incident power sensitivity analysis of the reactor indicated that a maximum concentrated solar power of 0.7 kW (4 MW/m² incident flux) yielded a sufficient temperature range of 340 °C to 920 °C inside the tube which is high enough for the biomass fast pyrolysis. Figure 4 presents the temperature contour plots for the three different solar cavity heights of 10 cm, 20 cm, and 30 cm simulated with a constant incident flux density of 4 MW/m² (0.7 kW of solar input), which is about 50% of the nominal concentrator capacity. The contour plots show that the solar cavity with 10 cm height attained a maximum temperature of 1270 °C at the center of the tube, but with a shorter heated tube length (length with T > 500 °C). For larger cavity heights such as 20 cm and 30 cm, longer heated tube lengths (T > 500 °C) are achieved with an effective heated tube length (T > 500 °C) of around 41 cm, for the 30 cm cavity height. However, the tube maximum temperature decreases relatively for the increasing cavity heights (from 1270 °C to 940 °C). This study highlights that a 0.7 kW pyrolysis reactor with a 30 cm solar cavity height presents a larger pyrolysis zone of temperatures above 500 °C, which would allow the injected biomass particles to effectively undergo fast pyrolysis conversion. The temperature range attained along the cavity zone for each of the increasing heights is 1219 °C to 1281 °C (10 cm cavity height), 994 °C to 1098 °C (20 cm cavity height) and 812 °C to 950 °C (30 cm cavity height) respectively. This shows that as the cavity height increases from 10 cm to 30 cm, the temperature gradient becomes more pronounced (62°C, 104°C, 138°C respectively), limiting further height increases beyond 30 cm as a homogeneous temperature zone is targeted inside the cavity.

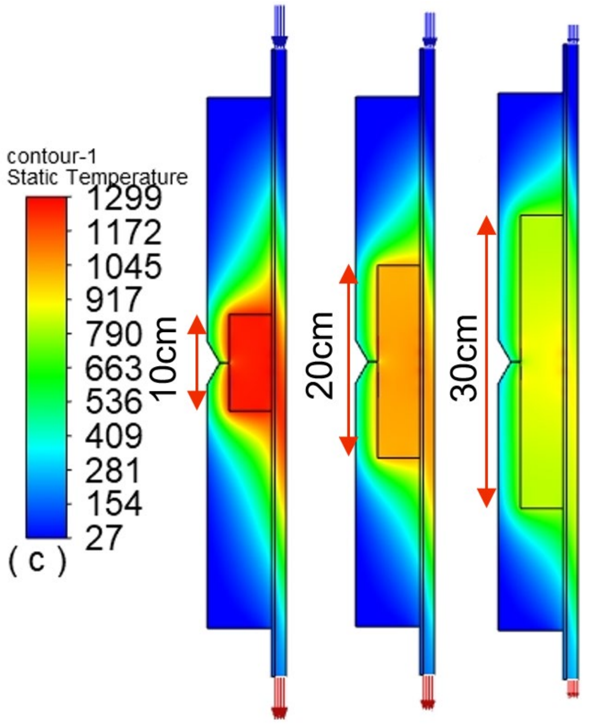

Figure 4. *2D model temperature contour results for different cavity heights*

4.2 3D Model

The 3D reactor model with a cylindrical solar cavity was beforehand simulated. The tube temperature along its axial length was extracted using longitudinal line probes at each radial section around the tube as shown in Figure 5a. Figure 5b presents the temperature plot for each line probe, along the receiver cavity zone of the reactor tube (30 cm length). A maximum tube temperature of 1100 °C at the tube front face (a1 line in front of the reactor aperture) is noted. However, there is a temperature difference of 100 °C between the longitudinal tube temperature profiles at the front (a1 line) and the back side (a2 line) (Figure 5b), which highlights that the heating of the reactor tube is not radially homogeneous in this 3D configuration.

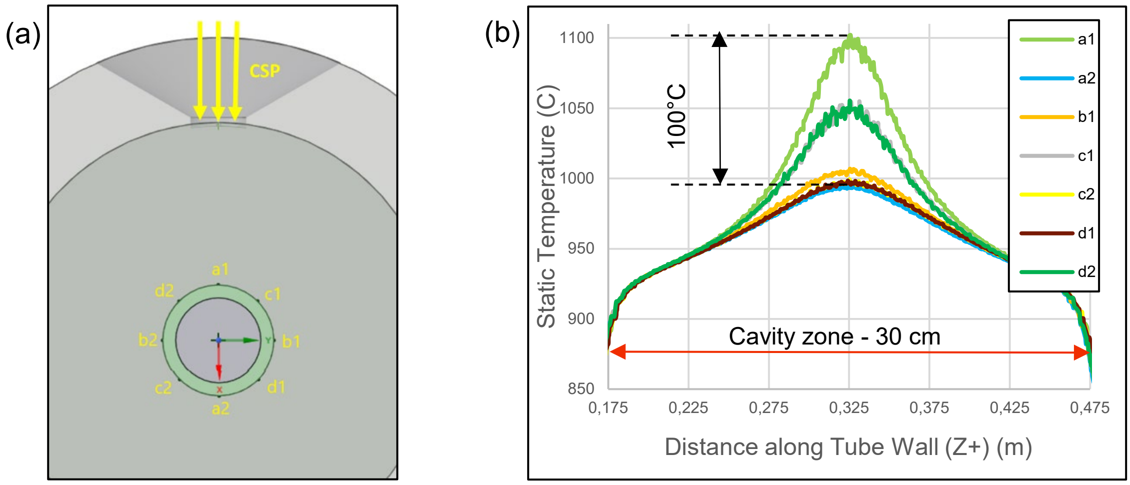

Figure 5. *(a) Cross-sectional plan of line probes, around the tube outer wall, (b) Static temperature plots of the line probes along the 30 cm cavity zone*

In order to evaluate the difference between the 2D and 3D models, the rector tube outer wall temperatures attained from the 2D axisymmetric model (in blue) and the 3D model (in red) were plotted in Figure 6a. It is observed that a maximum temperature of 1100 °C is attained at the tube center of the 3D model while a maximum temperature of 950 °C was reached in the 2D axisymmetric model. Both the red and blue temperature curves of Figure 6a display relatively stable temperatures along the solar cavity zone of 30 cm height, which is also observed in the temperature contour plots of Figure 6b.

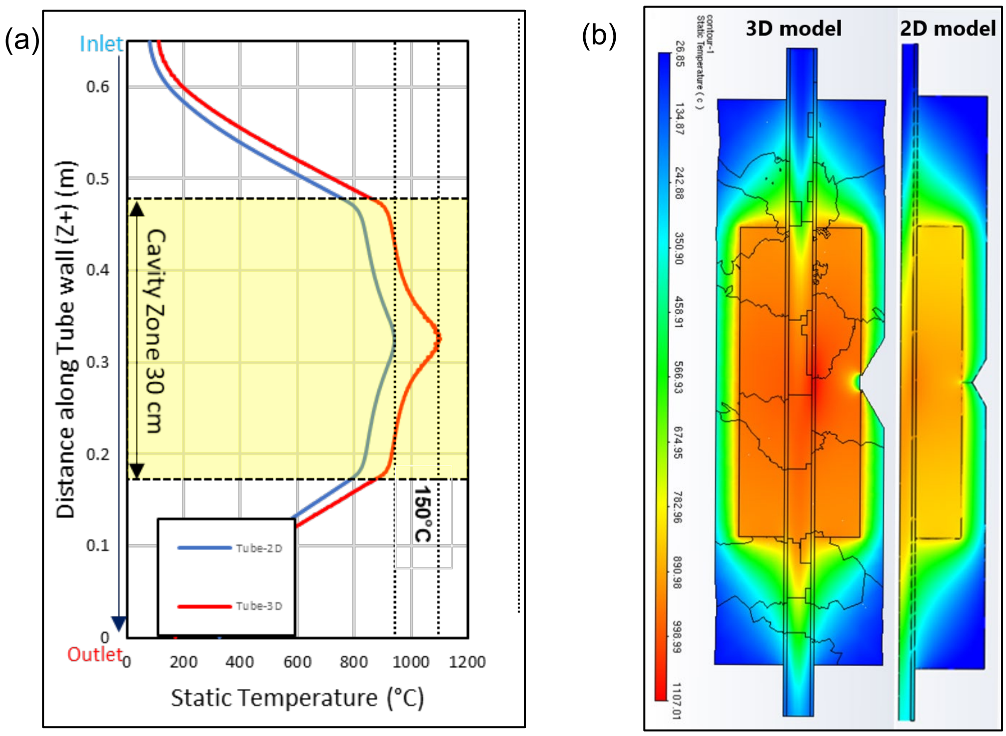

Figure 6. *(a) Static temperature plots of 2D axisymmetric and 3D cases along the tube outer wall, (b) Temperature contour results of the 3D and the 2D axisymmetric cases*

Even though the two irradiated surfaces of 2D and 3D models were of the same surface area, a temperature difference of 150 °C was still observed at the tube center as shown in Figure 6a. This difference in temperatures between the two cases arises from the fact that the heat dissipation occurred differently in the 2D axisymmetric CFD model and the 3D CFD model. In the 2D axisymmetric model the heat dissipation occurs around the reactor tube as shown in Figure 7a, while in the 3D model, the heat dissipation occurs only across the irradiated solar orifice (Figure 7b). This geometry difference that was imposed to run a 2D axisymmetric simulation also leads to a lower insulation around the 2D model due to the V-shaped solar entry instead of a conical shape for the 3D simulation (enabling larger radial insulation out of the cone). Hence, higher tube temperatures are reached on the 3D model, which also highlights radial temperature inhomogeneities. The 2D axisymmetric approach is thus limited for the reactor analysis, as it imposes geometric adaptation and cannot capture the varying radial temperatures of the reactor.

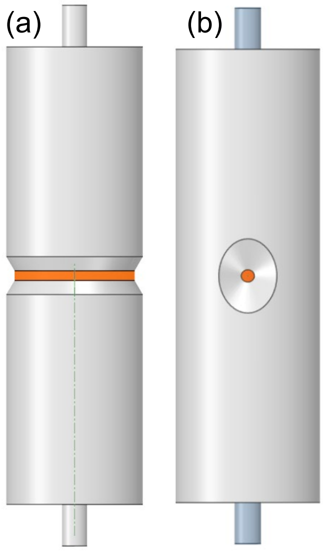

Figure 7. *(a) Cylindrical flux entry surface of 2D axisymmetric model, (b) Circular flux entry surface of 3D model*

4.3 Optimised 3D Model

The reactor model with the optimised solar cavity was then simulated. Figure 8 presents the temperature plot of line probes, along the receiver cavity zone. A maximum tube temperature of 1440 °C at the tube front face (a1 line) is observed, which is 340 °C more than for the previous 3D model. The temperature plots of Figure 8 indicate a lower temperature difference of 50 °C around the tube which tends to be relatively homogenous as compared to that of the first 3D reactor model (Figure 5b). The lower cross-sectional area of the optimised cavity results in a higher insulation thickness at the reactor back leading to a lower heat loss and better radial temperature homogeneity (Figure 9a).

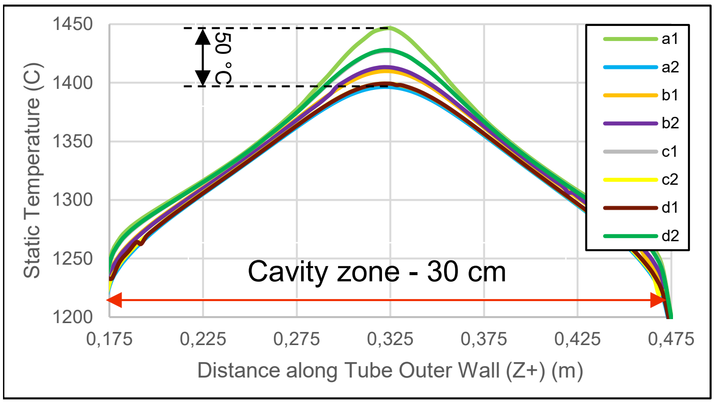

Figure 8. *Static temperature plots of the line probes along the cavity zone (30 cm) of the optimised 3D model*

As the temperature reached with the optimised 3D model was higher than the target value, it was also simulated with 0.35 kW input power. Figure 9b shows the temperature contour obtained. A maximum temperature of 975 °C is reached and the tube is heated beyond 500 °C, over a 52 cm length. This design could be suited for solar fast pyrolysis of biomass.

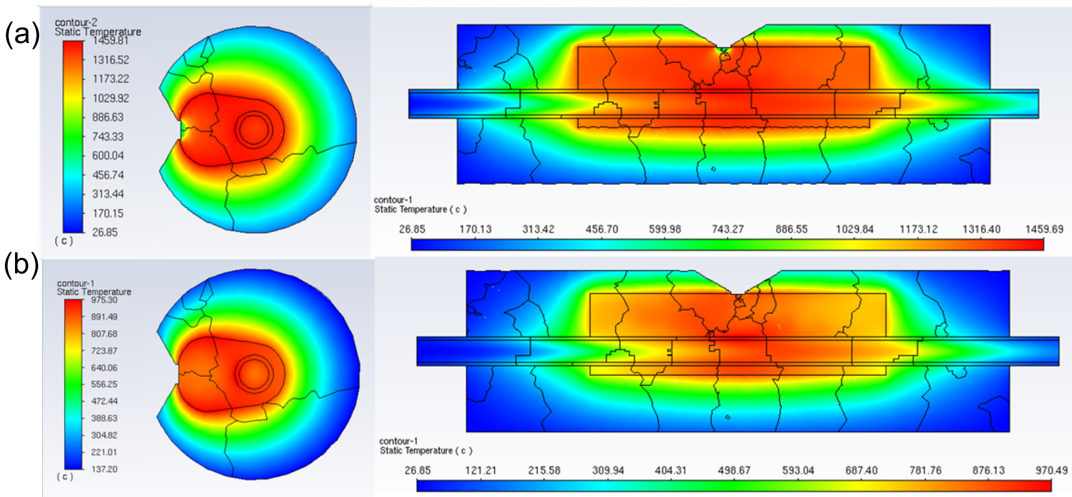

Figure 9. *(a) Static temperature plot of the optimised 3D model at 0.7 kW and (b) Static temperature plot of the optimised 3D model at 0.35 kW*

5. Conclusion

Solar-assisted pyrolysis at low temperatures is a promising technology for biofuel production without any potential carbon emission. This iterative thermal study and optimization of the drop-tube reactor through CFD simulations bring to a solar reactor design, capable of maintaining a minimum temperature of 500 °C, for a length of 50 cm along the heated tube. Following the thermal study of the reactor, a particle study using the Discrete Phase Model (DPM) is under progress with the injection of discrete biomass particles into the tube along with the argon fluid with the aim to study the particle residence time, path flow, and heating rate. In addition, the implementation of the pyrolysis chemical mechanism onto the biomass particles through user-defined functions (UDFs) is under consideration. Jointly, an experimental reactor prototype is under construction at the PROMES-CNRS laboratory, which is provisioned for further testing and validation of the results attained from the numerical analysis.

Data availability statement

Data is available upon request to the authors.

Author contributions

Vignesvar Krish Subramani: Conceptualization, CFD simulations, Methodology, Analysis, Writing. **Sylvain Rodat**: Conceptualization, Supervision, Funding Acquisition, Technical guidance, Writing – Outline and Draft Revision. **Stéphane Abanades**: Conceptualization, Supervision, Technical guidance, Writing – Outline and Draft Revision.

Competing interests

The authors declare that they have no competing interests.

Funding

We acknowledge funding by the European Union through the Horizon project Circular Fuels (ID: 101118239)

References

[1] Circular Fuels Website, < https://circularfuels.eu/ >
[2] Joardder, Mohammad U. H., Halder, P. K., Rahim, A., Paul, N., 2014. Solar Assisted Fast Pyrolysis: A Novel Approach of Renewable Energy Production, *Journal of Engineering*, 252848, pp.9. https://doi.org/10.1155/2014/252848
[3] Zeng, K., Gauthier, D., Soria, J., Mazza, G. and Flamant, G., 2017. Solar pyrolysis of carbonaceous feedstocks: A review. *Solar Energy*, *156*, pp.73-92. https://doi.org/10.1016/j.solener.2017.05.033
[4] Makkawi, Y., Yu, X. and Ocone, R., 2019. Parametric analysis of biomass fast pyrolysis in a downer fluidized bed reactor. *Renewable energy*, *143*, pp.1225-1234.https://doi.org/10.1016/j.renene.2019.05.077
[5] Artur Bieniek, Wojciech Jerzak, Marcin Gajek, Aneta Magdziarz, 2023. Numerical investigations of biomass pyrolysis with partial oxidation in a drop tube reactor, Journal of Cleaner Production, 401, pp.136774.https://doi.org/10.1016/j.jclepro.2023.136774