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Experimental Validation of Two Numerical Models of a Solar-Powered Multiple Air Jets Impingement Tube Heater

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1. ABSTRACT

This paper validates experimentally two numerical models of solar-powered tube heater that uses air impingement jets to heat steel tubes in the powder-based coating process as they move axially. A test rig is built to evaluate the thermal performance of the tube heater and validate both, its ANSYS *FLUENT Dynamic Mesh* model which simulated a moving target and ANSYS *FLUENT Transient Thermal* model which simulated a moving heat source. Results showed the experimental results to agree with those of the numerical models with an R^2-value of 0.983-0.997 and error fit of 3-10% for tube velocities of 0.033-0.1 m/s.

2. INTRODUCTION

The iron and steel industry was the second-highest energy consumer in EU exceeding 550 TWh in 2015 [1]. Its processes require 92% of their heat at high temperatures above 400 °C and 4.5% (16.6 TWh in EU) at medium temperatures of 150-400 °C [2]. To the author's best knowledge, no solar thermal energy systems have been integrated to this industry despite the available solar thermal technology for the processes of medium temperature [2]. One of the processes in the iron and steel industry that can be considered for the application of solar thermal energy is the powder-based coating process of steel tubes. It uses electric-based induction heaters to heat the tubes to a high temperature of 240 °C as they move axially before they are powder coated, leading to high greenhouse gases emissions [3]. A novel solar-powered tube heater was developed to reduce the use of the current induction heater in a powder-based coating process in Romania. The tube heater was designed and optimised numerically to employ multiple air impingement jets to effectively heat the moving tubes without interrupting the coating process [3]. In a previous study, two numerical models, the ANSYS FLUENT Dynamic Mesh *(NM1)* and ANSYS FLUENT Transient Thermal *(NM2)* models*,* were developed to evaluate the performance of the tube heater with a moving tube. The paper showed the tube heater to heat the tube to a temperature of 76 °C, reduction of GHG emissions by of 2.15 gCO_2e per each 1-meter tube processed [4].

The aim of this study is to experimentally validate the numerical results of the two numerical models of the tube heater simulated in [4]. Firstly, a test rig is built to evaluate the thermal performance of the tube heater. Secondly, four tests with different tube velocities are carried out and the experimental results are compared to the numerical results. Finally, an uncertainty analyses was conducted to assess the potential impact of equipment uncertainties on the results.

3. METHDOLOGY

Figure 1 presents the test rig which was set up to include the novel tube heater with extended inlet, a hot air loop, high temperature hoses, a steel tube with attached thermocouples and a data logger. The hot air loop contains an electric duct air-heater and a fan to produce hot air at the required flow rate and temperature. The tube heater was manufactured based on the optimum design obtained from the parametric analysis. It was connected to a hot air loop

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using high-temperature hoses which are well insulated to reduce thermal losses. Furthermore, a $15D_{air\text{-}inlet}$ extended inlet of the tube heater was installed to ensure fully developed flow. A pitot tube was used to monitor the air velocity at the inlet and nine thermocouples were strategically installed at critical locations including the air inlet, two outlets and around the tube to capture the temperature distribution in the system. Finally, a steel tube is moved axially through the tube heater with the help of the rollers and fourteen thermocouples were soldered to its surface to monitor the tube's temperature rise and report to the data logger.

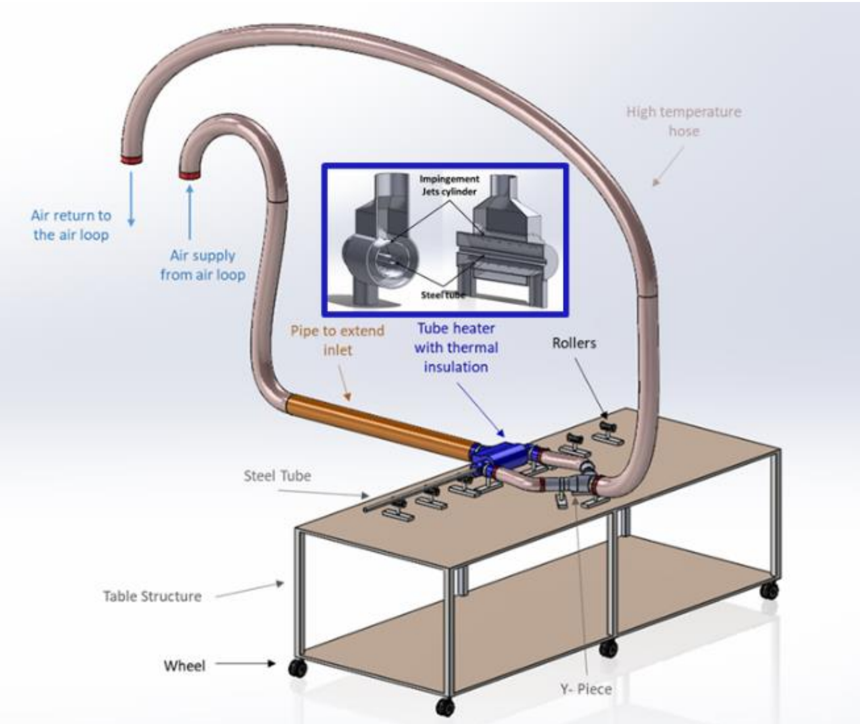

Fig. 1 Test rig

Four tests were carried out with tube velocities of 0.033, 0.05, 0.075 and 0.1 m/s and the temperature rise was obtained and compared to that of the two numerical models. Each test was repeated three times to ensure high results accuracy. Finally, the uncertainty of the results was calculated using Equation 1, which calculates the uncertainty of each reading, U_x, based on the error factor of the equipment used, S_x, and the reading obtained, X.

$$U_X = \frac{S_X}{\mathrm{X}} \quad (1)$$

4. RESULTS

Figure 2 compares the experimental and numerical results of the tube heater test with a moving tube. The experimental results were found to complement the results both numerical methods, the FLUENT dynamic mesh method and the FLUENT-Transient Thermal R-squared reaching 0.9971 and 0.9969, respectively, fitting within an error bar of as low as 3%. The R-square value can be seen to decreases to 0.9836 and 0.9834, respectively, with the error bar increasing to a value of 10% as the tube velocity decreases from 0.1 to 0.033 m/s. This is due to the human error introduced by moving the tube manually which increased with slower tube velocities. Considering that both models achieved an R-squared value exceeding 0.979 and error fit within 10%, it was concluded that both numerical methods are valid. It is important to note that NM1 was seen to overpredict the average temperature of the steel tube, whereas NM2 underpredicted it (Figure 2). Numerical models are expected to overpredict results as they neglect the thermal losses present in the experimental model. Hence, it can be concluded that NM1 present more precise results compared to NM2, complimenting the results found in [4].

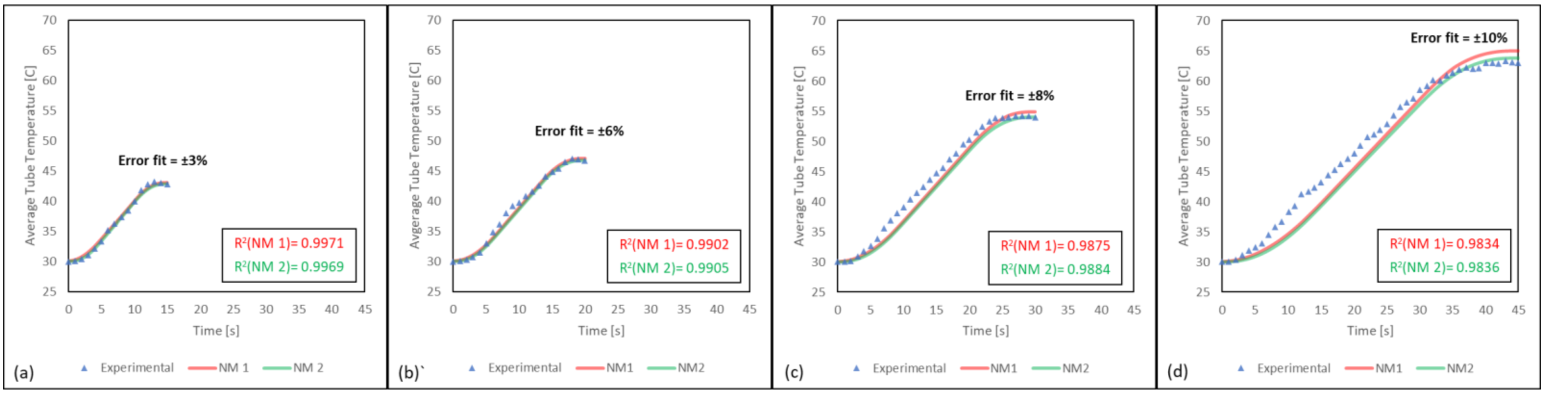

Fig. 2 Experimental validation of the numerical models with moving tube at *0.1 (a), 0.075 (b), 0.05 (c) and 0.033 (d) m/s*

Sources of uncertainty were found in the two equipment employed in the experimental tests, the pitot tube used to measure the air velocity and the thermocouples used to measure the temperature of the steel tube and air. These were found to reach ±2.5% for the pitot tube, ±1.8-2.2% for the thermocouples used for measuring the air temperatures and ±4.5-7.5% for the thermocouples used to measure the steel tube temperature. These values are well within the acceptable range of below 10%, as defined by Taylor [5].

5. CONCLUSIONS

This paper presented the experimental validation of two numerical models of novel solar-powered tube heater with a moving steel tube. A test rig was built to evaluate the performance of the tube heater with a moving steel tube. Results showed the experimental results to compliment the numerical results with an R-squared value of 0.983-0.997 and an error fit of 3%-10% for different tube speeds. The uncertainty of the experimental results were identified in the pitot tube and thermocouples with an error factor below 7.5%, confirming the validity of the results. It was concluded that although NM2 was less computationally expensive, NM1 provided more accurate and detailed results.

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