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THERMOCOUPLE INFLUENCE ON HEAT TRANSFER COEFFICIENT MEASUREMENT

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ABSTRACT

This paper investigates the influence of thermocouple installation on the measurement of heat transfer to the reciprocating compressor cylinder wall. The research employs simulations and experimental data to evaluate various aspects of thermocouple installation, focusing on how different mounting methods affect the accuracy of surface temperature measurements. Results indicate that while thermocouple mounting methods do influence surface temperature values, these differences are significantly smaller than the thermocouple resolution, making them difficult to detect in practical measurements. The study also highlights that variations in the calculated Heat Transfer Coefficient (HTC) depend heavily on the HTC evaluation process, which requires improvement for more accurate assessments.

Keywords: Compressor, Heat Transfer, Thermocouple

1. INTRODUCTION

Reciprocating compressors are widely used in various fields where compressed gas is needed. Especially in refrigeration, this type of compressor is popular for its versatility. It can be used in domestic refrigerators as well as industrial-scale chillers. Efficiency of a compressor consists of three main parts – electrical, mechanical, and thermodynamic. For reciprocating compressors, electrical efficiency can reach up to 90%, mechanical efficiency up to 95%, while thermodynamic efficiency is around 80%, offering the most room for improvement. One of the primary factors reducing thermodynamic efficiency is the overheating of the medium, which accounts for up to 50% of thermodynamic losses (Ribas et al, 2007). Overheating occurs mainly due to heat transfer to and from the walls and the cylinder head, both in the suction chamber and directly in the cylinder. This results in an increase in gas volume, reducing the amount of gas entering the cylinder and thus decreasing also volumetric efficiency. Identifying and understanding the heat transfer process in a compressor is therefore key to improve efficiency.

Due to the complicated access to the cylinder itself, limited space, and partially aggressive environment caused by lubricating oil, experimentally determining heat fluxes, which characterize heat transfer, is challenging. These thermal processes are highly dynamic, with both the direction and the amplitude of heat flux changing significantly with high frequency.

To measure heat flux in such systems, coaxial thermocouples are often used (Reichelt et al, 2002 and Irimpan et al, 2015). Their distinctive design provides very low response times making them ideal for these applications (Olivier et al, 1995). Coaxial thermocouples are installed in a way that allows them to measure the inner wall temperature. From the changes in this surface temperature, heat flux is determined. This approach requires the body to meet the conditions of a semi-infinite solid, meaning that heat transfer is mainly one-dimensional. Additionally, it is necessary to ensure that temperature fluctuations on the surface do not affect the internal temperature of the body (Incropera et al, 1996). According to Heywood (1988), these fluctuations in ICE are dampened at a depth of just 1 mm. Therefore, it is safe to assume that fluctuations with lower amplitude found in compressors, will dampen at a similar or smaller depth. To ensure the one-dimensional nature of heat transfer, it is also essential to minimize heat transfer in the direction perpendicular to the thermocouple's axis. For that reason, a layer of insulation can be installed between main body and a thermocouple. This layer can by in a form of a Teflon tape or a plastic insert. In compressor, there is an electromagnetic noise from power supply and motor that these thermocouples are prone to picking up (Reichelt et al, 2002). Such an insulation layer can then serve double purpose by shielding the thermocouple from the noise.

Material properties are important factor in heat transfer. Coaxial thermocouples can be made in all ordinary types, but thermal properties of these materials will still be different from those of compressor cylinder which is usually made of cast iron. For that reason, even though coaxial thermocouples are ideal for measuring temperature changes in a compression chamber, their different material properties make it unclear whether they provide reliable data for instantaneous heat flux determination. This issue can be further accentuated by introducing an insulation layer in the form of a plastic insert.

This paper presents a numerical simulation mimicking the flow in the compressor cylinder in order to identify influence of certain materials on the determination of instantaneous heat flux.

2. METHODS

The geometry for the simulation is rather simplified and should represent situation in the compressor cylinder. Air flows along the length of a 3 mm thick cast iron wall that has 3 cylindrical cutouts (Figure 1). Each cylinder represents a coaxial thermocouple. One is of the same material as the surrounding wall. The two remaining are set with the same properties as MCT 19 type E coaxial thermocouple (Dr. Müller Instruments, Germany). One of them is mounted directly in the wall (Thermocouple 1), the other through a plastic insert (Thermocouple 2). All the cylinders are installed the same way a thermocouple would be in a compressor cylinder - they are flush with the inner surface of the wall.

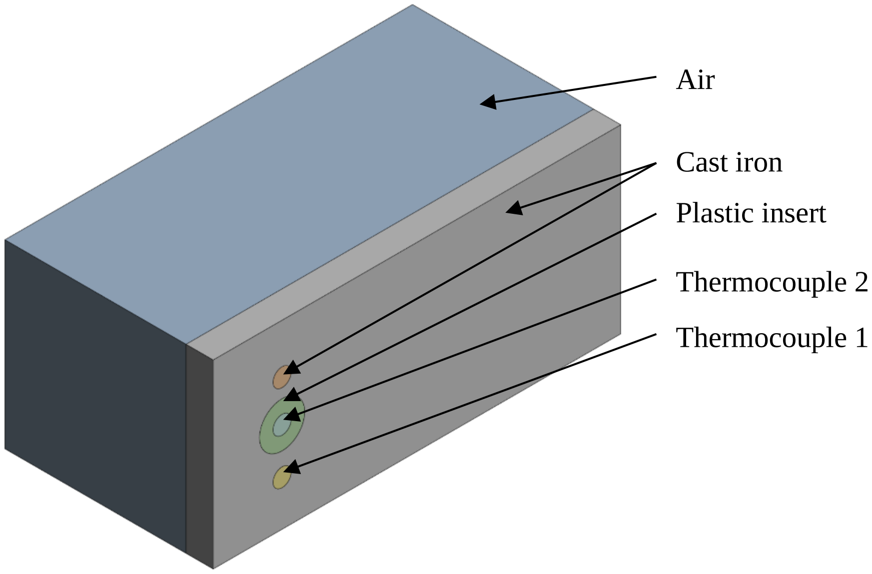

Figure 1 Geometry

The computational mesh is made in Ansys Mesh and consists of 615k polyhedral cells. Size of the cells is set to 1 mm, 0.75 mm and 0.5 mm in air, cast iron wall and cylindrical parts respectively. In the air domain, there are 10 prismatic layers on all peripheral walls.

2.1. Simulation setup

The inlet and outlet conditions of air are set on the sides perpendicular to the cast iron wall. The inlet is closer to the thermocouples and is set as a velocity inlet with a constant velocity value of 2.5 m/s. The value is determined as a piston mean velocity of an EK 4-2 reciprocating compressor (Orlik, Czech Republic). Pressure outlet option is set for the outlet.

Table 1 Inlet Temperature Variation

Pressure Ratio [-]	Suction Temperature [°C]	Discharge Temperature [°C]
4.1	35	105
8.7	40	170

To simulate conditions experienced in the compressor, air temperature on the inlet varies by time from suction to discharge temperature in a sine manner with a frequency of 141.4 rad/s, this corresponds to 1350 rpm at which said compressor operates. Two operating conditions are simulated, and the temperature variation is deducted from the real operation for two pressure ratios. Values of suction and discharge temperature with corresponding pressure ratio are listed in Table 1.

Other surfaces are set to wall conditions, with the outer surfaces of the cast iron and the thermocouples set to convection with a heat transfer coefficient of 10 W/m²K to mimic the real conditions of free convection around the cylinder. The thermal properties of all wall components are listed in Table 2. The plastic insert material is a resin used for 3D SLA printing. The Type E thermocouple is a combination of chromel and alumel.

Table 2 Thermal properties of used materials

Material	Density [kg/m3]	Specific Heat [J/kg K]	Thermal Conductivity [W/m K]
Cast Iron	7200	447	43
Type E Thermocouple	7835	420	22
Plastic Insert	1210	1210	0.3

The simulation was carried out using ANSYS Fluent 2024 R1 software. The simulation was transient with 10^{-5} s time step and was performed for total time of 0.5 s. Number of iterations per time step was set to maximum of 20. All the residues had convergence criteria set to 10^{-4} with all of them meeting the criteria well.

A temperature monitor is set for all the inner surfaces of the cylindrical bodies to monitor the temperature variation. This serves as an input value for further calculations.

2.2. Semi-infinite solid assumption

The surface temperature data, obtained from CFD, are processed similar way like a surface temperature data obtained by a direct measuring of surface temperature using coaxial thermocouples. These sensors measure the temperature at the surface of a material, and the measured temperature history can be analyzed to infer the heat flux.

The semi-infinite theory is a fundamental concept in heat transfer that provides a simplified model for analyzing transient heat conduction in solids. It assumes a material with one surface exposed to a heat flux while the rest of the material extends infinitely in the unchanged temperature (Incropera et al, 1996). The theory establishes a relationship between the heat flux, the thermal properties of the material (thermal conductivity and diffusivity), and the measured temperature history, hence offers a convenient framework for analyzing the temperature response of a surface-mounted thermocouple to a sudden change in heat flux.

To determine the validity of using the semi-infinite solid model for heat flux calculations, a comparative analysis is conducted. The depth at which the temperature fluctuation within the solid material becomes negligible is computed. This calculated depth is then compared against the actual thickness of the object wall. This assessment is carried out under two distinct boundary conditions: convective heat transfer with heat transfer coefficients of 300 W/m²/K and 1000 W/m²/K, and a scenario involving periodic heating at the wall. Relative temperature changes ΔT_{rel} inside the examined material are described using the following equations for periodic heating (Eq. 1) and periodic convection (Eq. 2):

$$\Delta T_{rel} = \frac{T(x,t) - T_i}{\Delta T} = exp\left[-x\sqrt{\omega/2\alpha}\right] sin\left[\omega t - x\sqrt{\omega/2\alpha}\right] \qquad \text{Eq. (1)}$$

$$\Delta T_{rel} = \frac{T(x,t) - T_i}{T_\infty - T_i} = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - \left[exp\left(\frac{hx}{k} + \frac{h^2 \alpha t}{k^2}\right)\right] \left[erfc\left(\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{k}\right)\right] \qquad \text{Eq. (2)}$$

Where $T(x,t)$ in K is the temperature for specified depth x in m and time t in s, T_i is the initial temperature in

K, α is thermal diffusivity in $m^2 \cdot s^{-1}$, h is heat transfer coefficient in $W \cdot m^{-2} \cdot K^{-1}$, k is thermal conductivity of selected material in $W \cdot m^{-1} \cdot K^{-1}$, ΔT in K is amplitude of the periodic heating and ω is angular velocity of the periodic heating in $rad \cdot s^{-1}$.

These equations are solved numerically to find the depth where the relative temperature change $\Delta T_{rel} < 0{,}001$. The time of observation for the Eq. (2) are set to $t = 0.044$ s, as it corresponds to time of one period for the compressor running at 1350 RPM, and $t = 0.5$ s for the expected time of measurement. The thermal properties of the cast iron and thermocouple used for the semi-infinite condition evaluation are the same as for the CFD simulation (Table 2).

Heat Flux Calculator software developed by SWT Aachen in cooperation with the Shock Wave Laboratory of RWTH Aachen University and distributed by Müller Instruments was used to calculate the instantaneous heat flux using the surface temperature values. The software calculation is based on semi-infinite solid theory and applies Eq. (3) (Olivier et al, 1995).

$$\dot{q}_s(t) = \frac{2\sqrt{\rho c k}}{\sqrt{\pi}} \sum_{i=1}^{n} \frac{T(t_i) - T(t_{i-1})}{(t_n - t_i)^{1/2} + (t_n - t_{i-1})^{1/2}} \qquad \text{Eq. (3)}$$

Where ρ in $kg \cdot m^{-3}$ is the surface material density and c in $J \cdot kg^{-1} \cdot K^{-1}$ its specific heat.

3. RESULTS AND DISCUSSION

The compressor running at 1350 RPM produces the cyclic thermal load with the period of 0.044 s. During that period, the information about the sudden temperature change penetrates to the depth of 1.3 mm for the cast iron wall and 1.0 mm for the thermocouple material. That is for the heat transfer coefficient $h = 300\ W \cdot m^{-2} \cdot K^{-1}$ (expected HTC value inside the compressor cylinder). If the periodic temperature change is applied directly at the wall surface, the oscillation is dampened to one thousandth of the amplitude within 3 mm for the cast iron and 2.2 mm for the thermocouple material. Comparing these values, we can conclude that the heat transfer could be treated as a semi-infinite for the cast iron walls thicker than 3 mm and for the thermocouple longer than 2.2 mm. The calculated depth values are presented in Table 3.

Table 3 Depths for the semi-infinite solid assumption

Material	x [mm]				
	Constant convection				Periodic heating
	$h = 300\ W \cdot m^{-2} \cdot K^{-1}$		$h = 1000\ W \cdot m^{-2} \cdot K^{-1}$		
	t = 0.044 s	t = 0.5 s	t = 0.044 s	t = 0.5 s	
Cast Iron	1.3	6.2	1.9	7.7	3.0
Thermocouple	1.0	4.6	1.4	5.8	2.2

Figure 2 shows the behaviour for the simulation case, where the peak air temperature reaches 170 °C with the mean temperature of 105 °C and amplitude of 65 K. The inlet temperature to the calculation domain is presented in Figure 2(a) together with the phase shifted temperature, representing the air temperature above the investigated area (thermocouples). Figure 2(b) shows the surface temperature of the Cast Iron, Thermocouple 1 and Thermocouple 2. The surface temperature differences between these three installations are within the 0.02 K and the temperature amplitude of the surface temperature signal is approximately 0.03 K. This means that both the differences and the signal amplitude are in orders of a magnitude smaller than thermocouple resolution. Hence the good signal conditioning will be required for the real measurements. The heat fluxes calculated using the HFC Calculator software are presented in Figure 2(c). The variations in the heat flux values are quite evident and they are caused by the different thermal properties of material (Cast Iron vs Thermocouple) and dimensionality of the heat conduction. Heat conduction in Cast Iron and Thermocouple 1 is of a 3D nature, whereas in Thermocouple 2 it is rather 1D. That is due to the plastic insert which partially works as an insulation. Figures 2(d) and 2(e) show the Heat Transfer Coefficient calculated from the heat fluxes and the temperature differences between surface temperature and domain inlet temperature and the surface temperature and the shifted temperature respectively. The differences between the HTC values are not so apparent except for parts where the air temperature signals are close to the surface temperature mean value and the small temperature differences produce substantial changes in the HTC. Moreover, the direction of the heat transfer is changing in this location. That affects the heat transfer coefficient curve behaviour when the HTC is changing from maximum positive to maximum negative value. But these values are out of the expected (physical) limits. It should be also noted that the dissensions of the heat transfer coefficient curves are different between Figure 2(d) and 2(e), so that the correct representation of the temperature difference must be found during the data processing.

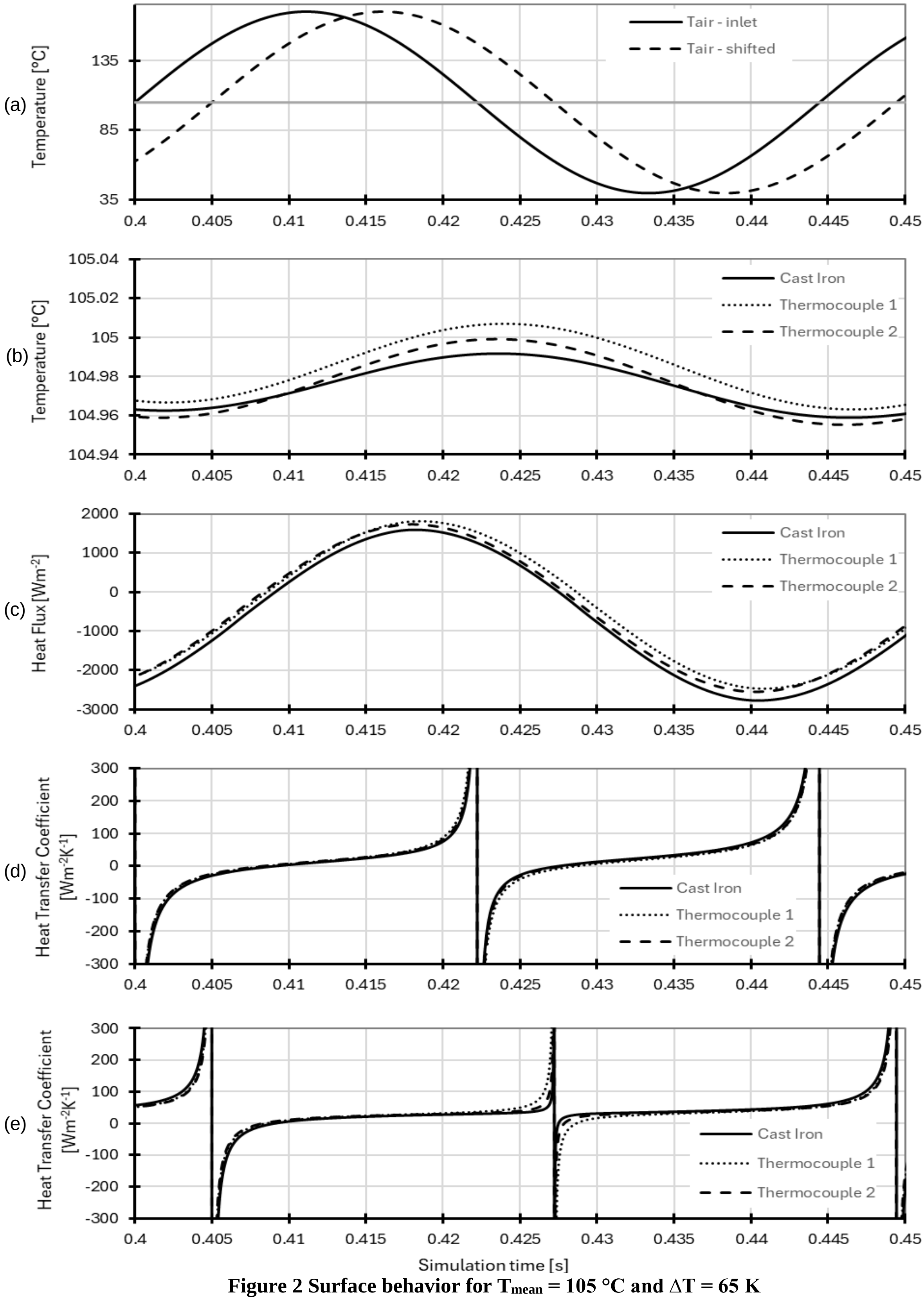

Figure 2 Surface behavior for T_{mean} = 105 °C and ΔT = 65 K

Figure 3 shows the simulation case with the mean air temperature of 70 °C and the amplitude of 35 K (peak temperature 105 °C). The curves behaviour is the same as for the previous condition. That means the thermocouple to surface interaction is independent on the air temperature.

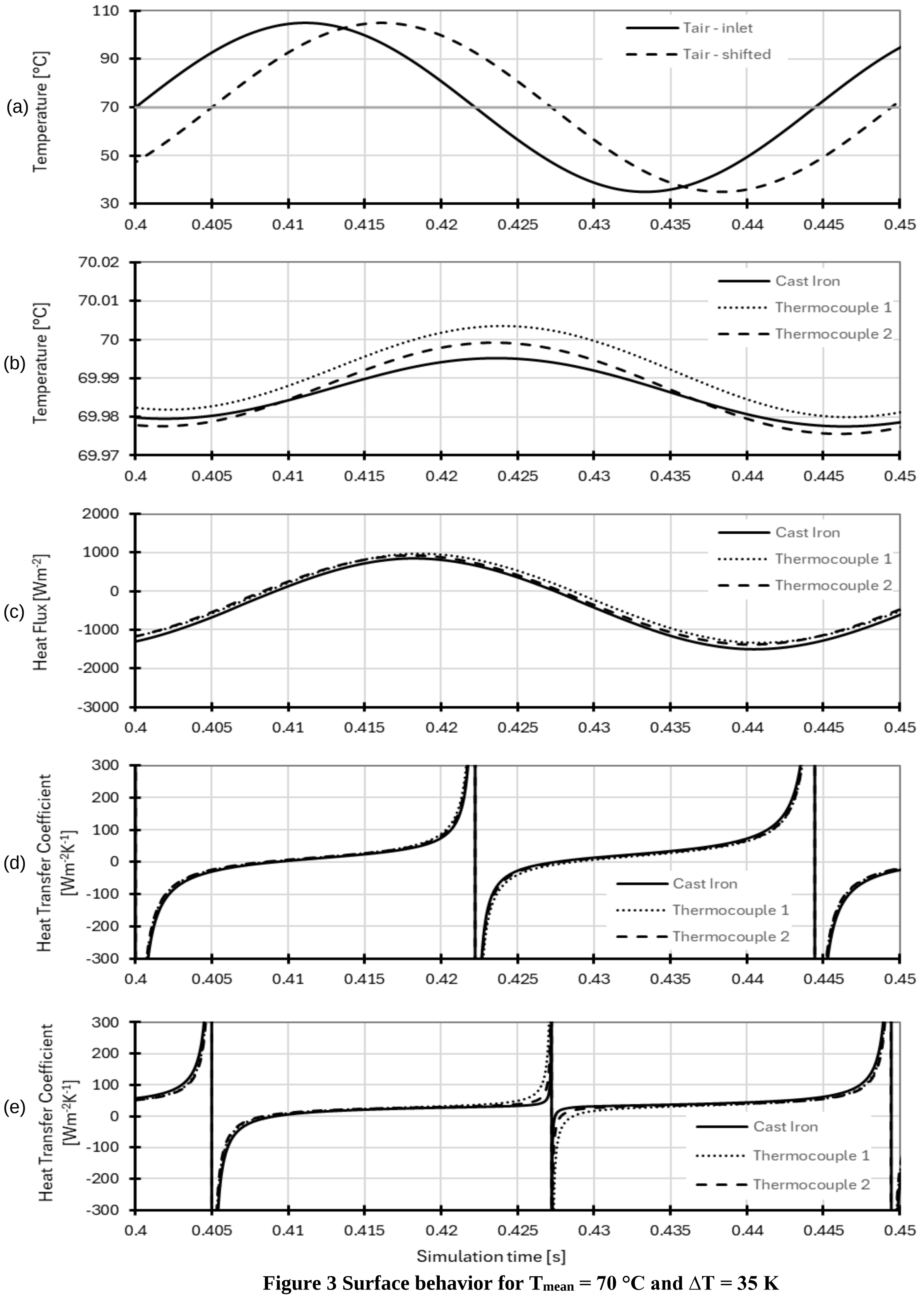

Figure 3 Surface behavior for T_{mean} = 70 °C and ΔT = 35 K

Figure 4 compares the values of the Heat Transfer Coefficient of the Cast Iron and Thermocouple 2 during the simulations with different temperatures level. There are no visible differences between the values of Heat Transfer Coefficient obtained from different inlet temperature profiles. Heat Transfer Coefficient is independent on the temperature level in case the temperatures amplitude and phase are the same and the temperature difference does not influence the air thermal properties dramatically.

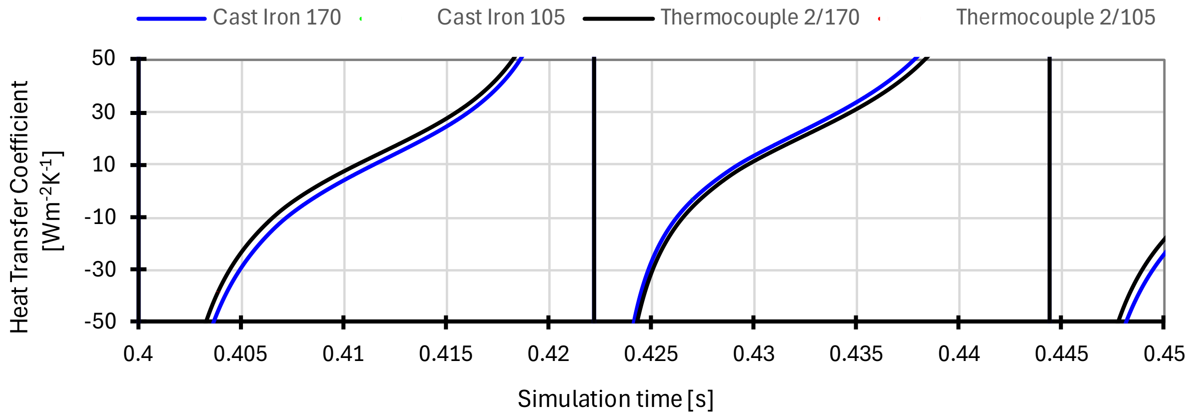

Figure 4 Heat transfer coefficient for different temperature levels

4. CONCLUSION

Two CFD simulation were realized to prove the influence of the method of the coaxial thermocouple mounting to the surface on the Heat Transfer Coefficient measurement.

The temperature profiles obtained from these simulations for the parts of surface representing the non-influenced (Cast Iron) surface, directly mounted thermocouple and the thermocouple with plastic insert were used to calculate the surface heat flux and heat transfer coefficient, using the commercially available Heat Flux Calculation software.

Results shows that the method of the thermocouple mounting influence the values of the surface temperature. The differences between the signals are in orders of a magnitude smaller than thermocouple resolution, hence it is quite challenging to identify such differences during the real measurement. The followed data processing exhibits the variation of the Heat Transfer Coefficient for different mounting methods. The differences in values are strongly dependent on the HTC evaluation process which should be improved.

HTC values calculated for the same place, using the same method are independent on the temperature mean value and oscillation amplitude.

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NOMENCLATURE

T	Temperature (K)	x	Depth (m)
t	Time (s)	α	Thermal diffusivity ($m^2 \cdot s^{-1}$)
h	Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ΔT	Temperature amplitude (K)	ω	Angular velocity ($rad \cdot s^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)	c	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)

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