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Comparative Analysis for Heat Transfer Performance of Heat Exchanger Single Tube Model with and without Plug-in

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Heat exchangers are devices that transfer heat between two or more fluids at different temperatures. In industrial production, the main function of the heat exchanger is to transfer heat from the higher-temperature fluid to the lower-temperature fluid, so that the temperature of the fluid reaches the specified target in the process flow and further meet the process requirements. This paper makes numeral simulation of the flow and heat transfer for the heat exchanger during operation, compares the heat transfer performance of the model with or without the plug-in. Besides, through the simulation of single tube model, it analyses the influence of the wind speed on the surface heat transfer coefficient and pressure of the plug-in tube and non-plug-in tube, compares their difference in the heat transfer performance, and states the key parameters in the heat exchanger design. In this paper, the computational fluid dynamics (CFD) software, FLUENT, was used to make simulation analysis of the heat exchanger, to discuss the temperature distribution of the heat exchanger, and analyse the impact of various environmental loads on the heat exchanger. This new simulation method can better improve the accuracy of the analysis, playing a certain guiding role in the future parameter design.

1. Introduction

The hot blast stove is the main auxiliary part for the equipment such as airflow drying, spray drying, fluidized drying, tower drying, tunnel drying and rotary drying etc. It is also the key device for warming greenhouses and livestock farms, and is widely used in different industries, including agricultural production, agricultural products and food processing, metallurgy, and building materials etc (Agarwal and Raja, 1996). Its metal walls can be used to separate the cold and hot fluids that exchange heat, allowing them to conduct heat through the walls. This type of heat exchanger is the most widely used one (Sparrow and Minkowycz, 1996). The heat exchange efficiency of the heat exchanger directly reflects the performance of the entire hot blast stove. Heat exchange equipment plays a crucial role in the chemical process, with its investment costs generally accounting for about 40% of all equipment investment, and its behaviour is also related to the normal operation and operating costs of the entire company. Therefore, the design of the heat exchanger has a direct impact on the technical and economic indicators of the whole drying equipment. In recent years, different types of heat exchangers have emerged in an endless stream (Sivashanmugam and Sundaram, 1999). Domestic and foreign experts have also done a lot of research on the mechanism, structural parameters, and performance characteristics of heat exchangers. Nowadays, with the rapid development of computer hardware and software, the finite element software has been widely used (Sun et al., 2017). By using the advanced analysis software to analyse the relevant design parameters, the technical requirements such as strength, stiffness and reliability can be ensured (Cucumo et al., 2016). Therefore, the purpose of this paper is to analyse the temperature field inside and outside of the heat exchanger, its thermal stress, and the generated thermal deformation in the two conditions: with and without plug-in; certain software was applied for model analysis. It shall provide some reference for the design of the heat exchanger (Zhang et al., 2016).

2. Main parameters for the analysed heat exchanger

The material of the heat transfer tube used in the heat exchanger is Q235.

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Table 1: Main dimensions of tube-type heat exchanger (mm)

Total length	Total width	Total height	Length of heat exchange tube	Inner diameter of heat exchange tube	External diameter of heat exchange tube	Thickness of tube wall	Lateral spacing of heat exchange tube	Horizontal equidistant number	Longitudinal spacing of heat exchange tube
4619	1600	2918	1950	43	53	5	90	22	70

3. Introduction to the co-simulation interface

This study is based on ANSYS Workbench 12.0 multi-physics collaborative simulation environment (AWE). The workbench is more user-friendly and can be imported into three-dimensional software models such as Pro/e and UG etc at the higher success rate of import (Touatit and Bougriou, 2018). It has a powerful automatic analysis function of assembly; the analysis involves more abundant physical space such as structural mechanics, fluid mechanics, electromagnetics, and multi-physics coupling, where some modules can easily carry out data transfer to complete the complex coupling analysis. In this paper, the three modules: Fluid Flow (Fluent), Steady-State Thermal (ANSYS) and Static Structural (ANSYS) were used for co-simulation, which starts with the fluid mechanics and heat transfer (Asif et al., 2017). Figure 1 depicts the co-simulation interface of Fluid Flow (Fluent), Steady-State Thermal (ANSYS) and Static Structural (ANSYS). From Figure1, it can be seen the friendliness, conciseness, standardization of operation steps on the Workbench interface as well as the free data transfer between different modules.

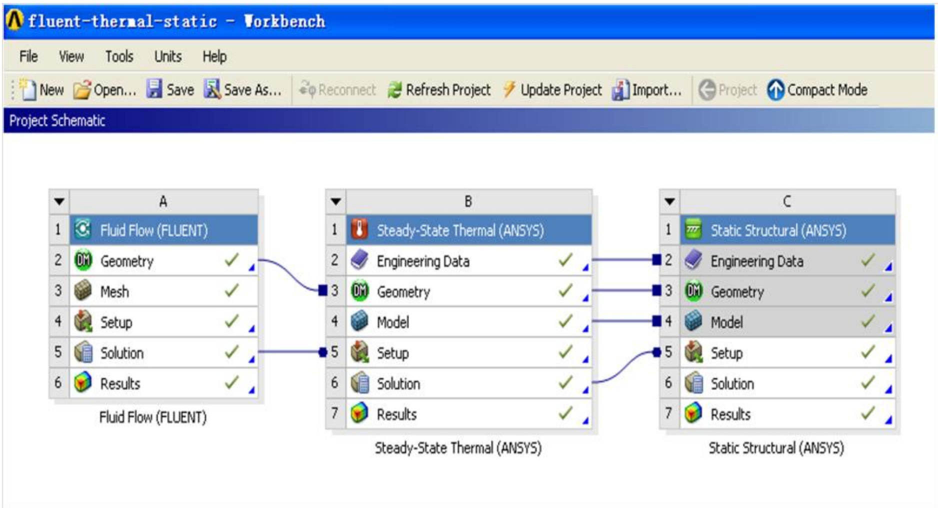

Figure 1: Co-simulation interface

4. Theoretical basis of thermodynamics

4.1 Heat transfer mode

There are three basic modes of heat transfer: heat conduction, heat convection and heat radiation. The actual heat transfer process is carried out in these three modes. In most cases, two or three heat transfer modes are performed at the same time. For the heat transfer of the heat exchanger, the study in this paper is also based on this theory (De et al., 2017).

4.2 Analysis type

Thermal analysis includes both steady-state thermal analysis and transient thermal analysis. Steady-state thermal analysis determines the temperature distribution and other thermal characteristics under steady-state conditions; the steady-state condition means the heat changes with time, which is negligible. Transient thermal analysis is used to calculate the temperature distribution and characteristics over time. For the heat exchanger in this paper, the steady-state thermal analysis was performed, because the heat exchanger works in the following process: firstly pass the cold air, and then the temperature of the heat exchanger gradually increases as that of flue gas increases, and finally enters into stable working condition of heat transfer. If making incorrect operation, the heat exchanger temperature will be too high, causing damage to the heat exchanger (Belloufi et al., 2017). The steady state thermal analysis of the heat exchanger is in accordance with its actual working conditions.

5. Relationship between tube heat exchange flow rate and pressure and its effect on surface heat transfer coefficient

5.1 Single tube model

Figure 2 shows the end view of non-plug-in model and the plug-in model. The outside is the flue gas channel, the middle is heat exchange tube, and the inside is the air channel for downstream heat exchange. Table 2 lists the model parameters.

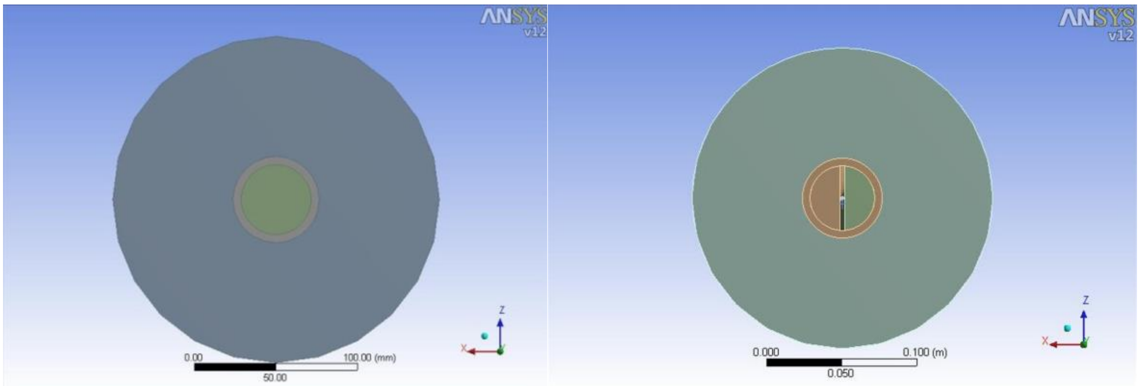

Figure 2: End view of non-plug-in model and plug-in model

Table 2: Model parameters (mm)

OD of flue gas channel	ID of flue gas channel	OD of heat exchange tube	ID of heat exchange tube	OD of air channel	Overall length	Plug-in thickness in air channel
200	53	53	43	43	1950	3

5.2 Boundary conditions

The inlet temperature of the flue gas is T=1073K; the speed is V=0.5m/s; the hydraulic diameter of the flue gas inlet: D=0.147m; the turbulent intensity of the flue gas inlet: I=7.3%; the hydraulic diameter of the air inlet: D=0.02462m; The air inlet temperature T = 353 K, and the air inlet velocity in the range of 2m/s-93m/s and the related air inlet turbulence intensity are listed in Table 3.

5.3 Calculation results

Table 3: Calculation results of the plug-in model and non-plug-in model at different air inlet speeds

Inlet velocity	Turbulence Intensity (non)	Total pressure difference at the inlet and outlet of air (non)	Surface heat exchange coefficient of the inner wall (non)	Turbulence intensity	Total pressure difference at the inlet and outlet of air	Surface heat exchange coefficient of the inner wall
2	5.7	10.15	7.08	6.1	26.49	9.25
5	5.0	43.77	12.21	5.4	96.06	14.58
10	4.6	138.74	19.21	5.0	297.65	21.91
13	4.5	217.66	22.51	4.8	465.61	25.32
23	4.2	594.10	30.83	4.5	1267.31	33.72
33	4.0	1140.17	36.66	4.3	2431.42	39.51
43	3.9	1851.33	41.02	4.1	3946.78	43.84
53	3.8	2724.68	44.44	4.0	5802.82	47.24
63	3.7	3757.81	47.22	3.9	8022.03	49.96
73	3.6	4949.56	49.54	3.9	10551.15	52.31
83	3.6	6295.84	51.50	3.8	13435.00	54.26
93	3.5	7798.11	53.18	3.8	16646.96	55.94

In order to facilitate the observation of the pressure difference and the variation trend of surface heat transfer coefficient with the wind speed, the pressure difference and the surface heat transfer coefficient in the above table were plotted by taking the wind speed as the x-axis and the heat transfer coefficient on the inner wall surface of the tube as the y-axis.

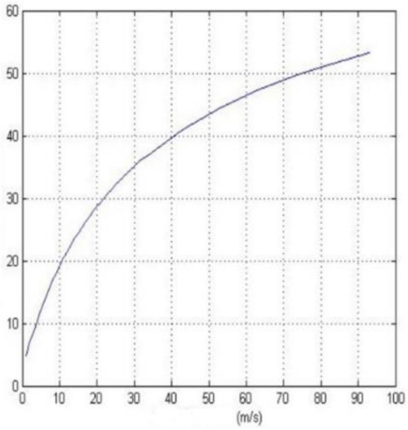

Figure3: Relationship between heat transfer coefficient (with plug-in) and air inlet wind speed

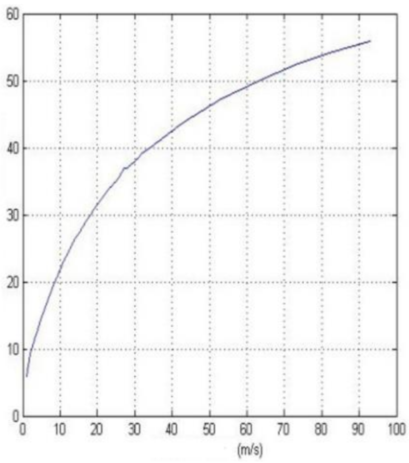

Figure 4: Relationship between heat transfer coefficient (without plug-in) and air inlet wind speed

Without plug-in, the polynomial fitting function is given as:

$$h_1 = -1.7854\,e^{-6}x^4 + 4.2397\,e^{-4}x^3 - 3.8406\,e^{-2}x^2 + 1.8706\,x + 3.6417 \tag{1}$$

where, h_1 - surface heat transfer coefficient without plug-in, W/(m2·K);
X- air inlet air velocity, m/s
With plug-in, the polynomial fitting function is given as:

$$h_2 = -2.0751\,e^{-6}x^4 + 4.8663\,e^{-4}x^3 - 4.2995\,e^{-2}x^2 + 1.9984\,x + 5.4151 \tag{2}$$

where, h_2 - surface heat transfer coefficient with plug-in, W/(m2·K);
X- air inlet air velocity, m/s
Taking the wind speed as the x-axis, the air inlet and outlet pressure difference as y-axis, it is plotted as shown in Figure 5 and 6.
Without plug-in, the polynomial fitting function is given as:

$$p_1 = 4.7907\,e^{-6}x^4 - 1.3879\,e^{-3}x^3 + 9.3369\,e^{-1}x^2 + 5.2276\,x - 4.9104 \tag{3}$$

where, P_1 - air inlet and outlet pressure difference without plug-in, Pa;

X- air inlet air velocity, m/s
With plug-in, the polynomial fitting function is given as:

$$p_2 = 1.0496\,e^{-5}x^4 - 2.9497\,e^{-3}x^3 + 1.9918\,x^2 + 10.9056\,x - 6.0487 \quad (4)$$

where, P_2 - air inlet and outlet pressure difference without plug-in, Pa;
X- air inlet air velocity, m/s

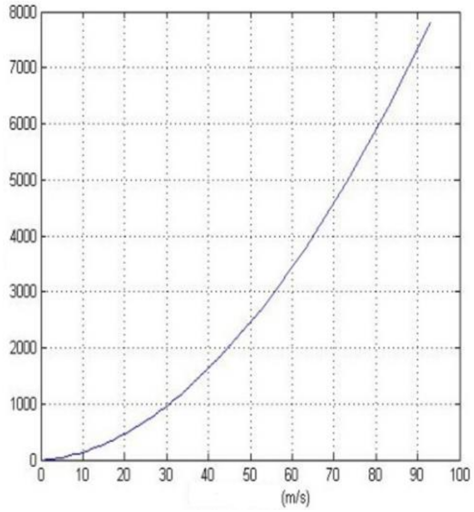

Figure 5: Relationship between air pressure drop (without plug-in tube) and inlet air speed

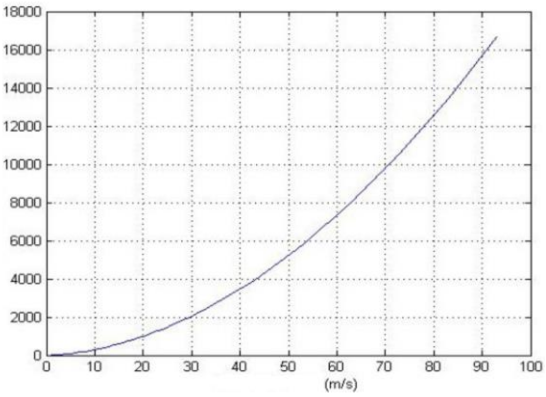

Figure 6: Relationship between air pressure drop (with plug-in tube) and inlet air speed

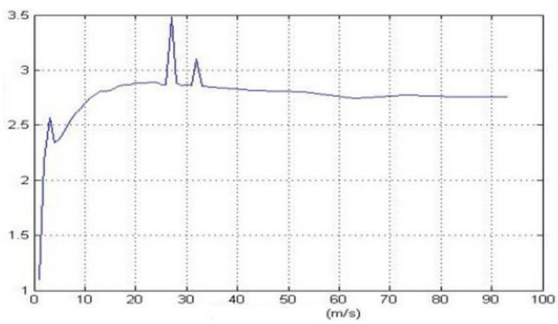

Figure 7: Surface heat transfer coefficient on the inner wall of plug-in tube and non-plug-in tube

From Figure 3 and 4, it can be seen that the heat transfer coefficient of the inner wall surface for the plug-in/non-plug-in heat exchange tube increases with the air flow rate in the tube, but the curve slope of the curve becomes smaller and smaller, that is, the heat transfer coefficient on the inner wall surface of the tube increases slower gradually. From Figure 5 and 6, the inlet and outlet pressure difference of the plug-in/non-plug-in model increases with the air flow rate in the tube, and the curve slope becomes larger and larger, i.e., the pressure differential at the inlet and outlet of air is increasing faster and faster. From Figure 7, the air inlet velocity is in the range of 1m/s-20m/s, and the plug-in has more and more obvious effect on improving the surface heat transfer coefficient of the inner wall; after 20m/s, the difference between these two is basically stable at the value of 2.8W/(m2·K).

6. Conclusions

In this paper, the single-tube heat exchange was simulated numerically, including the influence of wind speed on the surface heat transfer coefficient and pressure difference of plug-in tubes and non-plug-in tubes, and also the difference in the heat transfer performance of plug-in and non-plug-in models was compared. Through comprehensive analysis of the tables and figures, the conclusions are made as follows；

(1) When designing the heat exchanger, the air flow rate in the tube should be controlled within 20m/s. If the air flow rate is over 20m/s, the surface heat transfer coefficient on the inner tube is not increased much, but the pressure is drastically increased, thus promoting the requirements for the fan;

(2) If the design of the heat exchanger is limited by space, the air velocity in the tube is higher than 20m/s. Then only by inserting the plug-in into certain section of the air inlet and directly using the light pipes for the other sections, the turbulent flow effect will still work in the tube. This can not only ensure a higher surface heat transfer coefficient of the inner tube, but also reduce the pressure, thus lowering the requirements for the fan;

(3) It is necessary to increase the air flow area by reducing the air speed, or to use short plug-in instead of the long one.

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