RECOVERING EXHAUST HEAT OF COMBINE HARVESTER THROUGH HEAT PIPE EXCHANGER FOR DRYING GRAIN
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面向联合收割机在机谷物干燥的热管换热器排气余热回收研究

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DOI: 10.35633/INMATEH-58-20

Keywords: *agricultural machinery; heat recovery; gravity heat pipe; grain drying*

ABSTRACT

A drying system powered by heat recovered from the exhaust gas of combine harvester using the gravity heat pipe heat exchanger (HPHE) was proposed to improve the fuel efficient of combine harvester. The full-load characteristics of diesel engine were obtained through bench test. The constant heat flux method was used to calculate the heat transfer performances of every heat pipe and then the influence of inlet air parameters at the cold-side of HPHE on the heat transfer process were analyzed by computational fluid dynamics (CFD) simulation under the rated condition (RC) and maximum torque condition (MTC). The results show: for both working conditions, the inlet air velocity has greater effect on the heat transfer performances than the inlet air temperature and the outlet air temperatures are all suitable for the grain drying; the overall heat transfer coefficient of HPHE is higher under RC compared with MTC.

摘要

为了提升联合收割机发动机能源利用率，提出一种采用重力热管换热器的柴油机尾气余热回收的联合收割机谷物干燥系统。通过柴油机台架试验获取某型号联合收割机柴油机包含排气特性在内的外特性。针对该柴油机常用的额定工况和最大转矩工况，通过将热管假定为定热源，采用定热流密度法获取的每一根热管的传热性能参数，然后将各热管的传热性能参数代入到CFD 仿真模型，计算出了重力热管换热器冷侧的空气入口温度和入口流速对换热过程的影响。研究结果表明：在两种柴油机工况下，进口风速对换热过程的影响要远大于进口风温；虽然柴油机在最大转矩工况工作时，换热器冷侧空气出口温度变化范围比额定工况窄，但是该风温也能够满足谷物干燥的需求；相比于最大转矩工况，当柴油机工作于额定工况时热管换热器能够回收更多的排气余热能且总传热效率也更高。

INTRODUCTION

The diesel engine is widely used in agricultural machinery such as tractor and combine harvester and it becomes the main cause of energy consumption and air pollution. Many researchers focus on the improvement in the energy utilization rate of diesel engine since the shortage of fossil fuel and environmental problems become more and more severe. Unfortunately, the normal thermal efficiency of diesel engine is only 42% *(Nwosu P N, Nuutinen M, Larmi M, 2014)* and most of its fuel energy is taken away by the mechanical friction and exhaust gas. As a result, recycling the exhaust heat of agriculture machinery is one of the most efficient ways to enhance the thermal efficiency of diesel engine. *Danel Q. et al (2015*) considered that using the water as the working fluid of Rankine-Hirn cycle to recover the waste heat of tractor is better than ethanol. *Kalinichenko, Havrysh, Hruban et al. (2018)* classified waste heat recovery systems of agricultural tractors and combine harvesters into three applications including heating and cooling generation, mechanical work and electricity generation for the purpose of analyzing different waste heat recovery technologies to be used in agricultural applications according to their technical and economic indicators. *Jiao Youzhou et al (2018)* made researches on recycling the waste heat of the jacket water and exhaust gas of combine harvester using different working fluids. *Bai Jiwei et al. (2008*) designed a shell and tube heat exchanger to recovery the waste

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heat of a tractor aiming at the realization of grain synchronal semi-drying system this tractor is equipped with, and their results showed reusing the waste heat could decrease the grain moisture content by 3 to 6 percent. *Fei Xiang, Li Wang, Xian-fang Yue (2011*) developed a vehicle-mounted heat pump–assisted fluidization drying system driven by the waste heat recovered from the jacket water of diesel engine and flue gas of the dying system, their analysis results showed that the actual specific diesel consumption can reach 0.081 (kg diesel)/(kg water).

The dominating technologies for recovering the waste heat on a diesel engine of combine harvester including utilizing the waste heat for heating purpose, power generation purpose, refrigeration purpose and so on (*Thombare, Dhananjay, Jadhav, Jaipal, 2013*). A waste heat recovery system for the purpose of drying grain while the combine harvester is reaping grain simultaneously was proposed in this article using the gravity heat pipe heat exchanger (HPHE) to recover the waste heat of exhaust gas. Then, the exhaust characteristics of the diesel engine were acquired through the engine bench test. Finally, the simulation study based on computational fluid dynamics (CFD) was made to achieve the effect of the cold-side working parameters of HPHE on the heat recovery performances (*Lucaciu, Ondine, et al, 2015*).

MATERIALS AND METHODS

GRAIN DRYING SYSTEM BASED ON THE GRAVITY HPHE

The energy of exhaust gas from the diesel engine can be divided into two parts: residual heat energy and residual pressure energy. Although the energy of residual heat energy is less than 100% and the method to recovery it is more complicated than the residual pressure energy, its utilization potential cannot be ignored (*LIU Jing-ping, FUJian-qin, FENG Kang, 2011*).The grain drying system powered by the waste heat of exhaust gas is shown in Fig.1. The gravity *HPHE* is mounted in the exhaust pipe of the diesel engine. When the diesel engine of combine harvester is working, the high-temperature exhaust gas rushes into the hot-side of the HPHE and is interacted with the gravity heat pipes. The heat pipes heat the air blown across the cold-side of HPHE by a blower and then the heated air is pushed into the grain drying chamber integrated with screw conveyor and grain collecting tank of the combine harvester.

Since the gravity *HPHE* exchanges the heat through the phase transition of working medium, it could reach higher energy transfer efficiency and has less influence on the flow resistance of diesel engine's exhaust gas than the conventional heat exchanger (*Zhang Biguang, ZHOU Yongdong, LI Xianjun, 2013*).

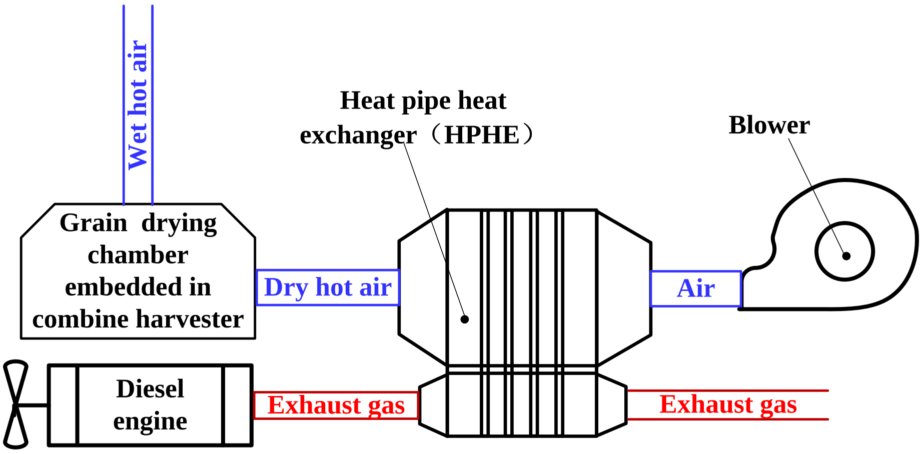


Fig. 1 - Layout of grain drying system powered by wasted heat recovered

CHARACTERISTICS OF DIESEL ENGINE

The parameters of turbo charged diesel engine equipped on the combine harvester is shown in Tab. 1. A test bench was setup to obtain the characteristics of the diesel engine as shown in Fig. 2. The test bench consists of diesel engine, eddy current dynamometer, fuel consumption test system, exhaust gas test system and cooling system. The cooling water temperature of diesel engine is kept constant at 90°C. A tube connects the fuel consumption meter and the external fuel tank. The temperature and pressure sensors are installed on the exhaust pipe after the turbo to detect the characteristics of exhaust gas in real-time (*Bandura, et al, 2019*). The temperature sensor is a k-type thermocouple and its allowable measurement range is 0-1300°C.

Table 1

Parameters of diesel engine

Item	Parameters
Engine Type	4 cylinders in line
Displacement [L]	1.9
Rated brake power [kW]	67(4000rpm)
Maximum brake torque [N·m]	202(1900rpm)
Intake type	Turbo charging

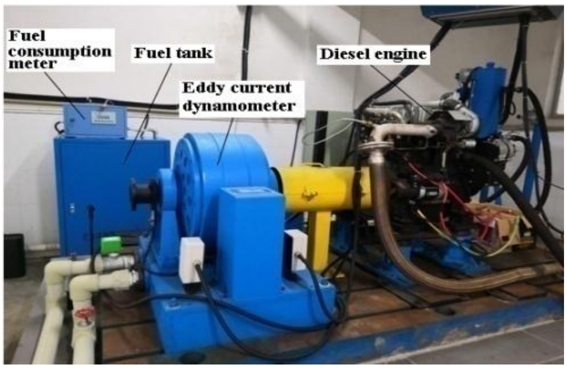
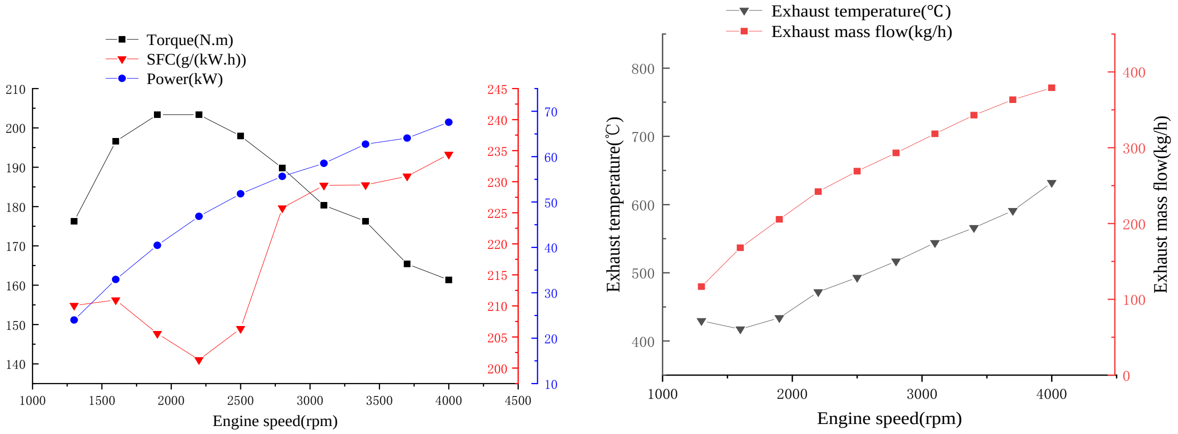


Fig. 2 - Test bench of diesel engine

The test process is in accordance with the national engine bench test requirements and the results of full-load characteristics are shown in figure 3.



(a) Power and fuel economy performances *(b) Exhaust performances*

Fig. 3 - Full load characteristics of diesel engine

SIMULATION MODEL AND METHOD

Simulation model. The design calculation should be done to determine the physical parameters of HPHE in order to establish the CFD simulation model.

Determining the parameters of *HPHE*. There are three restrictions to determine the parameters of HPHE as follows:

(1) The working condition of diesel engine. The exhaust gas temperature and flow rushing into the hot-side of *HPHE* change with the working condition of diesel engine. The maximum torque working condition of diesel engine is selected and the exhaust gas temperature and flow are 707 K and 205.5 kg/h respectively.

(2) Since the exhaust gas may contain the sour gases such as the sulfur oxides, the temperature of exhaust gas at the *HPHE* outlet should be above the dew point of the exhaust gas to avoid condensing the acid to erode the *HPHE*.

(3) The air flux through the cold-side of HPHE should be high enough to meet the demands of drying grain and the air temperature at the outlet of the HPHE should not be too high to increase the crack ratio of grain (*Kuang Peng, 2016*). For the purpose of designing the *HPHE*, the air flux is set as 812.16 kg/h and the air temperatures at inlet and outlet of the HPHE are set as 293 K and 333 K respectively.

The parameters of HPHE are acquired according to the above requirements and reference (*ZHANG*

Jun, ZHANG Hong, 2000) and they are listed in Tab.2.

Table 2

Parameters of HPHE

Item	Value
The number of heat pipe	14
arrangement	4-3-4-3 (regular triangle)
Working fluid	water
Wall material of heat pipe	carbon steel
Overall heat transfer coefficient [m^2·°C]	16.67
Heat transfer loss rate	0.07

CFD simulation model. Since the real process of fluid flow and heat transfer in the *HPHE* is very complicated, in order to simplify the simulation model, the following assumptions are made:

(1) the heat pipes are regarded as fixed heat source neglecting the phase transition of working fluid in the heat pipe and the heat transfer performances of heat pipes are determined by the constant heat flux method as shown in the section "Constant heat flux method";

(2) the process of fluid flow and heat transfer in the *HPHE* is steady and the fluids in the *HPHE* are incompressible;

(3) the physical property parameters of fluid are not changeable with its temperature;

(4) the radiation heat exchange is ignored.

The simulation model of *HPHE* can be simplified as Fig.4 shows because the construction, the arrangement of heat pipes and the fluid computation domain of *HPHE* are symmetrical.

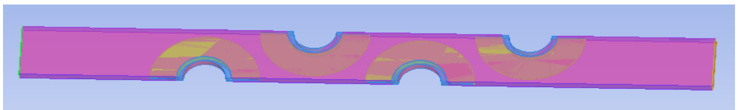


Fig. 4 - Simulation model of HPHE

Constant heat flux method. Heat transfer of *HPHE* is achieved through the phase transition of working medium in the heat pipe. If the temperature of the working medium and the heat flux of heat pipe at evaporation zone are given, then the heat transfer performances of the condensation zone is determined. Vice versa, if the temperature of the working medium and the heat flux of heat pipe at evaporation zone are given, then the heat transfer performances of the condensation zone is determined. Therefore, setting the heat flux of heat pipe's inner surface as constant combined with coupling source item to simulate the heat transfer process of *HPHE* could separate the cold-side and hot-side of HPHE independently and it is a common and effective method (*Vasylkovska K.V., et al, 2019*).

The heat transfer process of *HPHE* should abide by the laws of energy conservation, mass conservation and momentum conservation. Supposing the fluid in the *HPHE* is incompressible and its physical property parameters do not change with its temperature, the mass conservation can be expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

where u, v and w are the velocity components in the direction of x, y and z respectively.

Setting the temperature T as the variable, the energy conservation of the *HPHE* can be expressed as:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}+\frac{\partial(\rho wT)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{k}{c_{\mathrm{P}}}\cdot\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_{\mathrm{P}}}\cdot\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_{\mathrm{P}}}\cdot\frac{\partial T}{\partial z}\right)+S_{\mathrm{T}} \tag{2}$$

where ρ is the fluid density; c_{p} is the specific heat capacity at constant volume; k is the heat transfer coefficient of the fluid; S_{T} is the viscous dissipation term used to represent the mechanical energy dissipation equivalent to energy loss due to the fluid viscosity, heat conduction and diffusion etc.

The momentum conservation equation is as follows:

$$\frac{\partial(\rho u)}{\partial t}+\operatorname{div}(\rho v\vec{u})=\operatorname{div}(\mu\operatorname{grad}u)-\frac{\partial\rho}{\partial x}+S_{\mathrm{u}},\quad \frac{\partial(\rho v)}{\partial t}+\operatorname{div}(\rho v\vec{u})=\operatorname{div}(\mu\operatorname{grad}v)-\frac{\partial\rho}{\partial y}+S_{\mathrm{v}},$$

$$\frac{\partial(\rho w)}{\partial t}+\operatorname{div}(\rho v\vec{u})=\operatorname{div}(\mu\operatorname{grad}w)-\frac{\partial\rho}{\partial y}+S_{\mathrm{w}} \tag{3}$$

where S_{u}, S_{v} and S_{w} are the generalized source items and they can be expressed as:

$$\begin{aligned} S_{\mathrm{u}} &= F_{\mathrm{x}} + S_{\mathrm{x}}, \\ S_{\mathrm{v}} &= F_{\mathrm{y}} + S_{\mathrm{y}}, \\ S_{\mathrm{w}} &= F_{\mathrm{z}} + S_{\mathrm{z}}, \end{aligned} \tag{4}$$

where F_x,F_y and F_z are the unit forces applied on the micro unit and the gravity is the only force concerned in this study, that is to say, $F_x=F_y=0$ and $F_z=-\rho g$. The S_x, S_y and S_z are usually very small quantities and $S_x=S_y=S_z=0$ for the incompressible fluid with the invariant physical parameters.

The constant heat flux method should obtain the initial heat flux of heat pipe in the first place, and then the initial heat flux will be put into the boundary conditions of the HPHE's wall to calculate the wall temperatures of evaporation and condensation sections of heat pipe. The heat transfer calculation formula in the national standard is adopted to obtain the iterative heat flux of heat pipe in next step and the wall temperatures are calculated again. The iterative calculation repeats until the end.

The initial heat fluxq_0 can be calculated as:

$$q_0 = \frac{Q}{NA_{\mathrm{f}}} \tag{5}$$

where N is the number of heat pipes equipped in *HPHE*; A_f represents the surface area of heat pipe evaporation section; Q is the total heat exchanged by *HPHE* and it can be expressed as:

$$Q = \frac{V_{\mathrm{h}} c_{\mathrm{p1}} \rho_{\mathrm{h}} \Delta T}{3600} \tag{6}$$

where: V_h, is the volume flow rate [m^3/h];

ρ_h - the density [kg/m^3]

c_{p1} - the specific capacity [kJ/(kg·°C)] of the exhaust gas of diesel engine;

ΔT - the temperature decrease after the exhaust gas rushing through *HPHE*.

The iterative heat flux q_i can be expressed as:

$$q_{\mathrm{i}} = \frac{T_{\mathrm{ei}} - T_{\mathrm{ci}}}{R_{\mathrm{i}} A_{\mathrm{f}}} \tag{7}$$

where subscript 'i' is on behalf of the row number of heat pipe in the HPHE; T_{ei} and T_{ci} are the wall temperatures of evaporation and condensation sections of every heat pipe in the corresponding row respectively; R_i is the heat resistance in the corresponding row.

CFD simulation setting. Although both working and structure parameters of the *HPHE* have effect on the heat transfer process, the influence of working parameters on the heat transfer process of a fixed structure *HPHE* is analyzed. The rated condition (*RC*) and maximum torque condition (*MTC*) of diesel engine are considered in the simulation because the diesel engine of the hydraulic driven combine harvester is always running under nearly steady condition, and the parameters of the two conditions are listed in table 3. In order to analyse the influence of air temperature and velocity at the cold-side of *HPHE* on the heat transfer performances, the air temperature varies from 15°C to 35°C with the step of 5°C and the air velocity is set as 1.5 m/s, 2.0 m/s, 2.2 m/s, 2.5 m/s and 3 m/s respectively.

Table 3

Parameters of diesel engine under RC and MTC

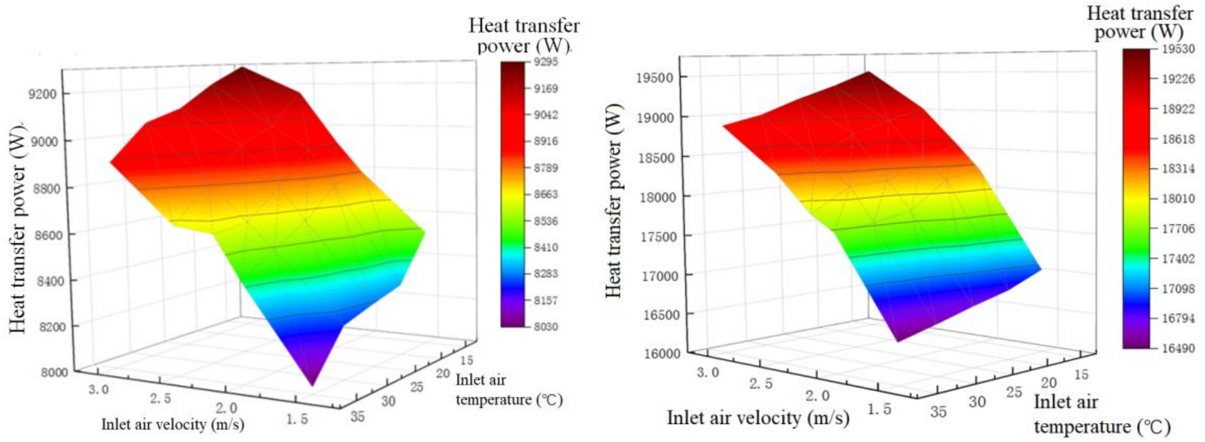
Working condition **Parameter**	**Rated condition (RC)**	**Maximum torque condition (MTC)**
Rotation speed (rpm)	1900	4000
Brake power (kW)	40.5	65.3
Brake torque (N·m)	203	161
Exhaust gas flow (kg/h)	205.5	379.2
Exhaust gas Temperature (°C)	434	632

RESULTS

The numeric simulation results are shown in Fig. 5 to Fig. 8. For both *RC* and *MTC* of diesel engine, the heat transfer powers increase with the rising inlet air velocity and falling inlet air temperature and reach their peak when the air velocity is 3 m/s and the inlet air temperature is 15°C as shown in Fig. 5.

The maximum heat transfer powers are 9.29 kW and 19.52 kW respectively.

The impact of inlet air temperature on the transfer heat power under *RC* is less than the one under *MTC* because the exhaust gas temperature is higher under *RC* in contrast to *MTC*.



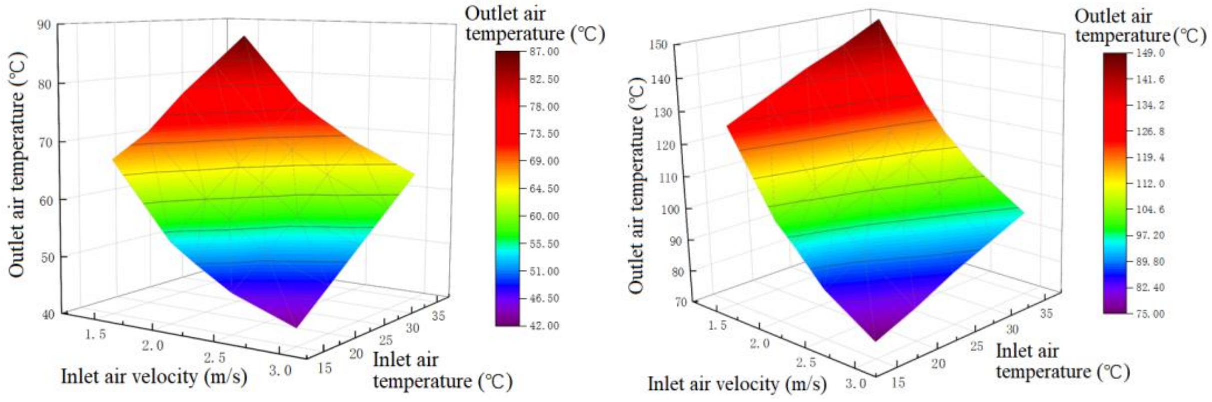
(a) RC *(b) MTC*

Fig. 5 - Influence of inlet air temperature and velocity on the heat transfer power

Temperature increase with the raising heat transfer power. When the heat transfer power is set as constant, the less air rushes into cold-side of the *HPHE*, the greater the temperature difference between the inlet and outlet air is. Therefore, the outlet air temperature reaches its peak as the air velocity is 1.5 m/s and the inlet air temperature is 35°C as shown in Fig.6.

The outlet air temperature ranges from 75°C to 149°C under the RC, and the range ability is wider in comparison with the *MTC*.

The outlet air temperature under the *RC* is too high to dry grain well although it can recover more energy from the exhaust gas of diesel engine compared with the *MTC*. The measures should be taken to reduce the outlet temperature for the *RC*.



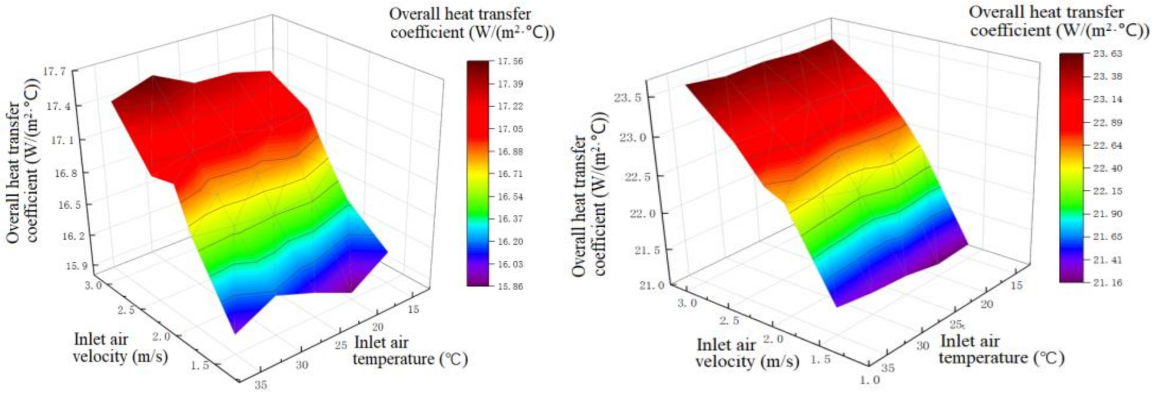
(a) RC *(b) MTC*

Fig. 6 - Influence of inlet air temperature and velocity on the outlet air temperature

The overall heat transfer coefficient is the indicator of heat exchange ability of *HPHE*. The overall heat transfer coefficient fluctuates with the inlet air temperature under *MTC* and the variation range is within 0.37 W/(m^2·°C) as shown in figure 7. The variation range of *MTC* is wider in comparison with the *RC* although their variation trends are the same because the air temperature is much higher under the *RC*.

The inlet air velocity has more effect on the overall heat transfer than the inlet air temperature and the overall heat coefficient increases rapidly with the increase of the inlet air velocity because the increasing inlet air velocity could enhance the turbulence inside the *HPHE* so that the heat pipe and air can exchange heat more fully.

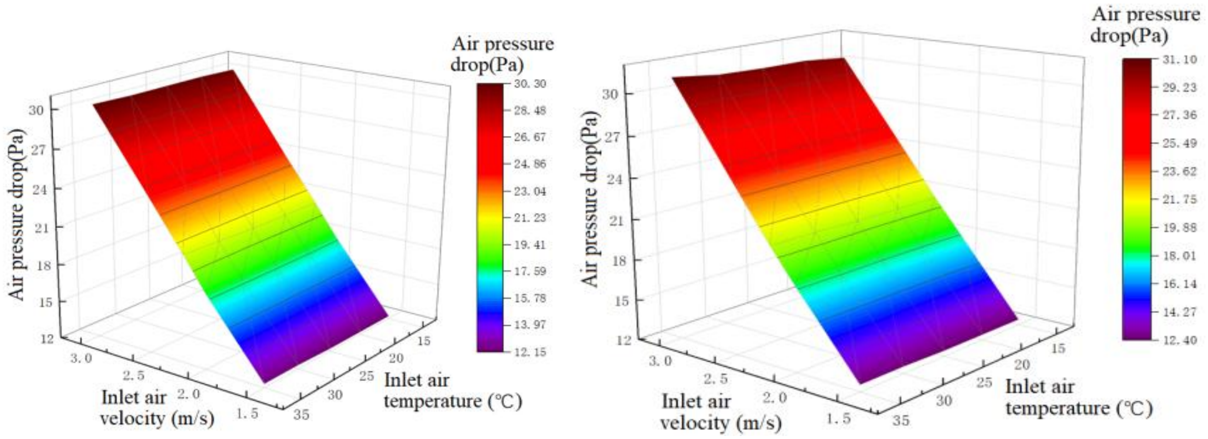
However, when the inlet air velocity is increasing above 2.5 m/s, the growth rate of overall heat transfer coefficient decrease since the inlet air velocity is higher enough to enhance the flow resistance. Therefore, it is necessary to maintain the inlet air velocity within 2-3 m/s *(Thombare, Dhananjay, Jadhav, Jaipal, 2013).*



(a) RC *(b) MTC*

Fig. 7 - Influence of inlet air temperature and velocity on the overall heat transfer coefficient

The impact of inlet air temperature and velocity on the air pressure drop at the cold-side of *HPHE* is shown in figure 8. The inlet air temperature has little influence on the pressure drop while the inlet air velocity has the significant impact on it. The higher the inlet air velocity is, the more the air pressure drops, which could increase the energy consumption of the blower (Fig.1).



(a) RC *(b) MTC*

Fig. 8 - Influence of inlet air temperature and velocity on air pressure drop

CONCLUSIONS

(1) For the RC, when the inlet air temperature and velocity are 3.0 m/s and 15~20^{o}C respectively, the outlet air temperature can meet the requirement of drying grain and the maximum heat transfer power can be obtained. Although the range of outlet air temperature is narrower under *MTC* in contrast to *RC*, the outlet hot air can also be suitable for the grain drying.

(2) The exhaust heat of diesel engine under *RC* can be recovered more and the overall heat transfer coefficient of *HPHE* is higher compared with *MTC*. However, the higher exhaust gas flow under *RC* would enlarge the pressure drop at the hot-side of *HPHE* to deteriorate the performances of diesel engine. Moreover, the exhaust gas temperature at the hot-side of *HPHE* could reach up to 632^{o}C under *RC*, so a high-temperature working medium in the heat pipes should be used rather than water (the working temperature of water is only 250°C) to prevent the possibility of the heat pipe explosion.

(3) The similar variation trends of both *RC* and *MTC* reveal the simulation process is feasible. The future work will focus on the working process in the heat pipe.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (grant number 31560344) and Science and Technology Project of Jiangxi Province (grant number 20181BBF68016).

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