PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Design and test of a novel wheat drying oven based on the real-time utilization of diesel engine waste heat

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Abstract: A small, novel wheat drying oven was designed, and tested in order to validate the possibility of recovering diesel engine waste heat as thermal energy. Prior to experiments, the theoretical probability was conducted, and it was confirmed that the thermal energy required for drying wheat could be satisfied by reusing the diesel engine waste heat. Three different experiment parameters, including air temperature, baffle angle, and drying time, were controlled to optimize the results. Based on the experiment data, the optimum temperature for drying wheat was 55°C, and the optimum baffle angle was 23.25°. The drying efficiency decreased as the drying temperature and drying time increased. The moisture content of wheat decreased from 26.0% to 20.0% with 55°C hot air when the proposed wheat drying oven was used. The test results demonstrated that the proposed oven could be made to work.

Subjects: Mechanical Engineering Design; Energy & Fuels; Manufacturing Engineering Design; Technology; Waste & Recycling

Keywords: wheat drying; diesel engine waste heat; drying oven; drying temperature; baffle inclination angle; drying time

1. Introduction

For wheat and other cultivated grain crops, drying and storage methods affect the quality and yield of the crops. Drying methods, in particular, are important when processing grain and other agricultural products. In recent years, China has experienced an increased use of grain dryers and
a rapid development of grain drying technology. Despite these advances, most grain crops are currently harvested using combines, which have an effective energy utilization rate of approximately 30% (Yu, 2011), and do not offer an independent drying function even though their exhaust gas heat accounts for approximately 40% of the fuel heat value (Liang & Liang, 2002).

Waste heat is generated during a diesel engine run time. Recovering waste heat can be taken via different methods, the common technology used for reusing waste heat is organic Rankine cycle (Chintala, Kumar, & Pandey, 2018; Hoang, 2018; Mat Nawi, Kamarudin, Sheikh Abdullah, & Lam, 2019; Nadaf & Gangavati, 2014; Shi, Shu, Tian, & Deng, 2018). The utilization of waste heat from diesel engine could contribute to saving energy and even money, it was calculated that 1 kW of electric power generation via diesel generators would result in approximately 1kW of heat rejection in the exhaust in remote Canadian mines (Baidya, De Brito, Sasmito, Scoble, & Ghoreishi-Madiseh, 2019).

Existing research regarding grain drying technology has been scattered and mostly focused on specific food products or systems for laboratory-scale testing. These studies have not developed a functional drying system prototype which is scalable to industry. The immediate challenge is to design a grain drying system that decreases operation costs, energy consumption, and emissions while maintaining or increasing product quality. The design proposed in this study, which aims to use the waste heat from a combine’s diesel engine to dry wheat, could result in lower operation costs, energy consumption, and emissions. This design could subsequently emerge as a leading grain drying technology that promotes high grain yields and adds value to China’s agricultural products.

Drying systems that are currently in use meet basic functional requirements, but fall short in achieving satisfactory levels of energy consumption, environmental pollution, product quality, and operational ease, control, and safety. At present, energy resources are limited, and resource-saving grain drying equipment needs to be developed urgently. In addition, most of these systems were developed before energy consumption, environmental emissions, and product quality requirements were strictly controlled. Although incremental improvements have been made to these existing drying systems to ensure regulatory compliance and marketplace competitiveness, many have likely reached their limits in terms of design and use. Hence, new drying system designs that directly address the existing focus on environmental protections, energy conservation, and economic benefit may now be warranted.

Drying system performance is assessed using various parameters. Generally, materials contain surface and internal moisture. The rate in which moisture is removed from the surface is related to the external heat and mass transfer rate because the control resistance of the drying rate is external to the material being dried. The external heat and mass transfer rate increase as the airflow rate and temperature increase or as humidity decreases. Any measure to reduce external resistance will result in an increase in the drying rate (Hemis, Singh, Jayas, & Bettahar, 2011; Qin, Fu, Wang, Liu, & Yan, 2017; Tadeusz & Mjumudar, 2005; Liu et al., 2004).

A substantial body of research has considered waste heat collection and utilization, but few studies have applied their findings to drying system designs. Yuan designed a carbon steel-ammonia double-blade heat pipe heat exchanger to recover heat from the exhaust gas emitted from an automobile’s internal combustion engine (Yuan, 1991). The inlet, outlet, and exhaust gas temperatures were 0–15°C, 65°C, and 260°C, respectively. Chen investigated the use of waste heat, geothermal resources, and a low-boiling-point working medium to achieve triangular circulation power generation (Chen, 2017). The approach generated electricity using lower temperature waste and geothermal heat, thus reducing heat emissions to the environment. Lu investigated the utilization of waste heat in the shipping industry and found that a ship’s air compressor station had significant potential for waste heat recovery (Lu, Zhang, & Liu, 2017). The full utilization of the waste heat would increase energy savings and economic benefits. Zhou analyzed a rapeseed drying system that used heat pipe technology to recover diesel engine waste heat (Zhou, 2015).
Using the system, the moisture content of the rapeseed was a little higher than 9%, the recommended moisture content for safe storage but still met the predefined drying system requirements, demonstrating the system’s feasibility.

For a combine used to harvest grains, waste heat from the diesel engine begins as a high-grade product but gradually converts to a low-grade product that is discharged during utilization, and this waste heat utilization process is inherently unstable. The selection of an appropriate heat transfer medium is important. The medium should be adaptable to temperature to reduce irreversible loss. Different media can be used for heat transfer in high- and low-temperature regions. For example, air can be used as the medium in a high-temperature region and organic matter can be used as the medium in a low-temperature region (He et al., 2014, 2012, 2014; Liu, He, Gao, Xu, & Xu, 2012; Luo, Zhang, Wu, & Liu, 2014).

In this study, the feasibility of using the waste heat from a combine’s diesel engine to drying wheat was investigated by using the principle of energy conservation, and the validity of this design through experimentation was tested.

2. Materials and methods

2.1. Theoretical possibility

With the wheat drying oven design fully conceptualized, the temperature and energy requirements for drying wheat by using diesel engine waste heat should be confirmed theoretically. Specifically, the temperature and energy requirements could be needed to reduce the moisture content of wheat about 13% (the average score of the commercial dryer in the market), for instance, from 26% to 12.5%, here 12.5% was the standard moisture for storage wheat.

The energy or heat required to reduce the wheat’s moisture content from 26% to 12.5% could be determined as follows (Wang, 1979):

\[ Q_1 = W \times C \times \Delta T \]  (1)

where \( Q \) represented the heat, \( C \) represented the specific heat capacity of water, it was 4.2 KJ/KG, \( W \) represented the wheat mass lost, same as the value of moisture lost, and \( \Delta T \) represented the varying temperature of water, here was from 45°C to 100°C (45°C was supposed as the lowest temperature of waste heat), and \( W \) could be calculated as follows (Liu, Wang, Ren, & Zhang, 2017):

\[ W = P \times \frac{M_1 - M_2}{100 - M_2} \]  (2)

where \( P \) represented the wheat mass processing from the feed port in per minute, here, the \( P \)-value was supposed to 30KG/MIN. \( M_1 \) represented the beginning moisture 26%, and \( M_2 \) represented the end moisture 12.5%.

Then, \( Q_1 = 30 \times \frac{26 - 12.5}{100 - 12.5} \times 4.2 \times (100 - 45) = 1069\text{KJ} \)  (3)

Considered the loss of energy in the actual situations, the thermal efficiency was supposed as 70%, so the thermal energy \( Q_d \) needed to reduce the wheat’s moisture content would be calculated by the follows:

\[ Q_d = \frac{Q_1}{0.7} = \frac{1069}{0.7} = 1527\text{KJ} \]  (4)

The fuel consumption and exhaust temperatures of diesel engines under different operating conditions are listed in Table 1. It was clear that exhaust gas temperatures could range from 300°C to 328°C when discharged from a diesel engine, which exceeded wheat drying requirements (the suitable temperature range for drying wheat was 40–70°C).
According to the principle of energy conservation, the heat balance equation of diesel engine could be calculated as follows (Zhou, 2015):

$$Q_t = Q_w + Q_s + Q_c + Q_o$$

(5)

Where $Q_t$ represented the total heat from a diesel engine, $Q_w$ represented the power caused by the engine, $Q_s$ represented the heat of the exhaust gas, $Q_c$ represented the heat taken by the cooler system, and $Q_o$ represented the other heat lost.

Also, the total heat $Q_t$ from a diesel engine could be determined as follows:

$$Q_t = m \times q$$

(6)

where $m$ represented the fuel consumption and $q$ represented the fuel heat value. When a combine's operating speed was 1701 rpm (the normal operating speed of a combine was 1000–2000 rpm, and 1701 rpm was the steady condition in the experiment), its fuel consumption, $m$ was 0.1165 KG, and the fuel heat value, $q$ for diesel was $3.3 \times 10^4$ KJ/L, and the density of diesel oil was 0.84 KG/L.

Under these conditions,

$$Q_t = 0.1165 \times \frac{3.3 \times 10^4}{0.84} = 4577KJ$$

(7)

The heat of the exhaust gas could be determined as follows:

$$Q_s = Q_t \times \mu$$

(8)

where $\mu$ represented the lost heat efficiency. Here, the lost heat efficiency was supposed as 35% (Liang & Liang, 2002), then,

$$Q_s = 4577 \times 35\% = 1602KJ$$

(9)

$$Q_s > Q_d = 1527KJ$$

(10)

Because the residual heat from the diesel exhaust exceeded the required heat to reduce the wheat's moisture content from 26% to 12.5% based on these formulations, the proposed wheat drying oven design was determined to be theoretically feasible.

### Table 1. Fuel consumption and exhaust temperatures of diesel engines under different operating conditions (Jiao, Tian, & He, 2017)

| Speed/rpm | Output power/kW | Fuel consumption/g | Temperature/°C |
|-----------|-----------------|--------------------|----------------|
|           |                 |                    | Inlet | Outlet | Exhaust |
| 2199      | 90.3            | 134                | 83.4  | 87.5   | 328     |
| 2000      | 90.6            | 128.5              | 84.2  | 88.7   | 309     |
| 1701      | 86.2            | 116.5              | 85.1  | 90     | 310     |
| 1602      | 82              | 109.5              | 85.7  | 90.8   | 314     |
| 1502      | 78.5            | 105                | 85.7  | 91     | 300     |
| 1399      | 70.7            | 95.5               | 85.7  | 91.3   | 309     |
| 1299      | 64.4            | 87                 | 85    | 90.8   | 314     |
| 1200      | 57.9            | 79.5               | 84.8  | 90.8   | 310     |

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### 2.2. Structure of wheat drying oven

The schematic and physical diagrams of the wheat drying oven are shown in Figure 1. And the wheat drying oven had been obtained a national invention patent in China in December 2018 (ZL 2018 2 0743868.4). Feed and discharge ports were located at the top and bottom of the reversible drying box, respectively. Three downward-turning, material-bearing baffles were vertically
staggered inside the drying box. The baffles were fixed on two sides of the box and a limiting bolt was located at the bottom of the baffle. Air inlets for introducing dry air were located along the two sides of the drying box. A honeycomb air outlet was located at the top of the drying box to ensure that the hot gas in the box was fully dispersed.

Wheat was automatically churned based on its own weight. The limiting bolt at the bottom of the baffle prevented contact with the adjacent baffle. To ensure effective wheat drying, the heating time could be adjusted by changing the bolt length, which changed the baffle angle.

2.3. Experimental methods used to validate design

The wheat, Zhengmai 366, was used in the experiments, and this kind of wheat had an impurity content of 1.2%. Prior to experimentation, the wheat was artificially humidified to achieve moisture contents of 26%, 31%, and 36%, which were consistent with the moisture contents of just harvested wheat.

The diesel engine (lr6a3l-22) used in the study was typical of the engines used in combines for domestic wheat harvesting and had a rated power of 67.5 kW. The diesel engine waste heat collection device which was used in the laboratory was made by the laboratory team ourselves (the leader was professor Jiao). The supplemental equipment included a grain moisture analyzer with a resolution of 0.1%, and a multi-function electronic scale. Using these facilities, the air temperature from the inlet of the drying box could be adjusted to 45°C, 50°C, 55°C, and 60°C.

A series of experiments were subsequently performed to reveal the effects of air temperature, baffle angle, and drying time on wheat drying. At first, the feed rate for the wheat was set to 0.5 KG/S (30 KG/MIN), and different air temperatures of 45°C, 50°C, 55°C, and 60°C were sequentially blown into the drying box as containing wheat with initial moisture contents of 26%, 31%, and 36%. Baffle angles kept unchanged. After repeated experiments, the optimal air temperature for drying wheat was chosen based on wheat moisture content measurements in the drying box. Then, six different baffle positions were sequentially used in the drying. The air temperature was held constant at 55°C, and the hot air was keeping to blow into the oven for 30 min. After repeated experiments, the optimal baffle angle was chosen based on wheat moisture content measurements. Lastly, wheat with an initial moisture content of 31% was used, and air with different temperatures of 45°C, 50°C, 55°C, and 60°C was sequentially blown into the oven. After repeated
experiments, the effects of drying time on wheat drying were determined based on wheat moisture content measurements taken at 5-min intervals in the drying box for up to 40 min.

3. Results and discussion

3.1. Air temperature effects on wheat drying

The resultant wheat moisture contents are shown in Figure 2 after drying at each of the different air temperatures when the feed rate for the wheat was set to 0.5 KG/S. Among the air temperatures considered (45, 50, 55, and 60°C), an air temperature of 55°C consistently produced the largest decrease in wheat moisture content (from 36% to 30.3%, from 31% to 25.5%, and from 26% to 20%), and thus provided the best wheat drying effect.

3.2. Baffle angle effects on wheat drying

As shown in Table 2, the moisture content of wheat basically was declined under certain baffle angle after drying for 30 min with 55°C hot air, but declined degrees were different, the highest declined degree happened in the group moisture 36%, average declined degree was 16.5%. On the contrary, the group of moisture 26% got the lowest declined degree, only about 6.8%.

As Figure 3 shown, it was clear that the angle 4 had the best drying effect under different moisture levels.

During experimentation, a mark was made on the inner wall of the drying box each time when the baffle position was changed. Using this mark and the right triangle formed by the baffle and vertical wall of the drying box, the corresponding baffle angle \( \theta \) was determined as follows:

\[
\theta = \sin^{-1} \frac{a}{c}
\]

Figure 2. Wheat moisture content at different air temperatures.

| Angles | 1 | 2 | 3 | 4 | 5 | 6 | Average |
|--------|---|---|---|---|---|---|---------|
| Moisture 36% | 21/15 | 21/15 | 20/16 | 18/18 | 18.3/17.7 | 18.7/17.3 | /16.5 |
| Moisture 31% | 19.5/11.5 | 19.4/11.6 | 19/12 | 18.6/12.4 | 19/12 | 18.8/12.2 | /12 |
| Moisture 26% | 21/5 | 20/6 | 18.9/7.1 | 18.3/7.7 | 18.5/7.5 | 18.7/7.3 | /6.8 |
where \( a \) represented the length of the triangle's side opposite to \( \theta \), and \( c \) represented the triangle's hypotenuse.

When the baffle angle position was at angle 4, \( c \) could be measured, here, \( a = 17.55 \text{ mm} \), \( c = 45 \text{ mm} \). Then, \( \theta \) could be calculated as follows:

\[
\theta = \sin^{-1} \left( \frac{17.55}{45} \right) = 23.25^\circ
\]  

(11)

### 3.3. Drying time effects on wheat drying

As shown in Figure 4, generally, wheat moisture contents decreased as the air temperatures and drying times increased. To the groups of lower air temperature 45°C and 50°C, the moisture decreased quickly with the added drying time during the first 20 min, and then it was decreased slowly with the drying time. To the groups of higher temperature 55°C and 60°C, the moisture was decreased quickly with the drying time during the first 15 min, then it was decreased slowly, and the moisture was kept unchanged after 25 min. It suggested that too high of an air temperature could adversely affect wheat drying efficiency with extended drying time, the reason was that the drying speed was affected by the decreasing speed of hot air dispersion in the oven.

### 4. Conclusions

A novel wheat drying oven was designed and validated to demonstrate the utilization of a combine’s diesel engine waste heat through a series of experiments using different air temperatures, baffle angles, and drying times. The experimental results were used to analyze the wheat's moisture content under different conditions. The optimum temperature for drying wheat was 55°C.
and the optimum baffle angle was 23.25°. It showed that wheat moisture contents decreased as the air temperatures and drying times increased, but different hot air temperature had different results when the drying time increased. Too high of an air temperature adversely affected wheat drying efficiency by extending drying times.

The moisture content of wheat decreased from 26.0% to 20.0% with 55°C hot air. Comparing the assumption from 26% to 12.5% in the theoretical study, the efficiency of the drying oven was not good for long-term wheat storage, but the objectives of this study were proved to be work. The collective results from this study demonstrated that the proposed drying oven that used diesel engine’s residual heat could be used to dry wheat. This novel design, with its theoretical basis, had the potential to decrease operation costs, energy consumption, and emissions while maintaining or increasing product quality.

Noted that the waste heat of diesel engine could not be fully utilized in practical applications; thus, empirical results could differ from theoretical results. The internal structure of the drying box and the selection of construction materials could also affect the empirical results. Building upon the findings from this study, future research will consider further improvements to the wheat drying oven design facilitated through various parameter adjustments.

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