Comparative investigation of performance of gas dryer and two other types of domestic clothes dryers

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Abstract
The moisture extraction rate (MER) and energy efficiency of domestic gas clothes dryers, heat-pump clothes dryers and electric clothes dryers were assessed. The assessment was performed with regard to five indices: the MER, specific MER, specific thermal energy consumption for dehumidification ($m_{SPC}$), energy efficiency ($\eta_1$) and primary energy efficiency ($\eta_1$). The effects of the dry mass of clothes ($m_{BD}$) and ambient temperature on the performance of the clothes dryers were evaluated. The experiments were divided into two parts. In the first part, the ambient temperature was 20°C, and $m_{BD}$ was set as 1.5, 2.5, 3.5, 4.5 and 6 kg. In the second part, $m_{BD}$ was 3.5 kg, and the performance of the dryers was tested at ambient temperatures of 5, 7.5, 10, 12.5, 15 and 20°C. The experimental results indicated that the gas dryer had the highest MER the heat-pump dryer had the best performance with regard to energy conservation and all three types of dryers had a higher MER and energy efficiency when the ambient temperature increased. The performance of the gas dryer was lower than that of heat-pump dryer when the temperature was 20°C. But when the temperature was < 9.5°C, the primary energy efficiency of the gas dryer was higher than that of the heat-pump dryer.

Keywords: domestic clothes dryer, performance assessment, moisture extraction rate, energy efficiency

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1. INTRODUCTION

Compared with natural drying in the air, clothes dryers have better performance for drying and sterilizing and do not affect the outward appearance of a town [1]. Therefore, domestic clothes dryers are widely used in developed countries. In the USA, 90% of families own clothes dryers. In Europe, 60% of families own clothes dryers. The typical electric clothes dryer has become the second-largest consumer of electricity among household appliances in the USA. If the net calorific value of natural gas is calculated as 35.04 MJ/m³, all residential clothes dryers in the USA annually consume approximately 43 million MWh of electricity and 13.4 billion m³ of natural gas, leading to carbon dioxide emissions of 32 million metric tons [2]. Domestic clothes dryers mainly include electric dryers, gas dryers and heat-pump dryers. In China, most dryers function as part of a washing-and-drying machine. Electric dryers are normally the least expensive among the three aforementioned types of dryers. Currently, coal-fired power generation is still the main source of electricity in China. However, the high utilization of electric dryers will increase the regional winter electricity load and exacerbate environmental pollution.
The usage of clothes dryers by ordinary families is increasing and customers increasingly tend to choose gas dryers. Compared with electric dryers, which are already widely used by ordinary families, the first heat-pump dryer (Electrolux) was invented by a European scientist in 1997. Schmidt et al. [3] and Klocke et al. [4] successfully applied the transcritical CO$_2$ process to drying heat pumps in 1997 and 2000, respectively. Thus far, many studies concerning the structure of electric dryers have been conducted [5, 7]. Pradeep Bansal et al. [8] noted that the electric dryer with a water-to-air finned-tube heat exchanger performs better with regard to energy efficiency and time consumption than the electric dryer with the electric elements of a standard tumbler. The energy efficiency of electric dryers is influenced by the ambient temperature and relative humidity, and the time consumption is mainly influenced by the dry mass of clothes and the heating power [9]. Similar to the domestic water heater, the condensing heat exchanger has been applied in the electric dryer [10]. New technologies for clothes drying have been studied, such as the use of thermoelectric elements [11] and waste heat from a spilt-type room air conditioner [12].

The performance of clothes dryers must be analysed using assessment indices. Researchers have performed many studies on indices for evaluating dryer performance. Various computer models have been proposed for evaluating the performance of clothes dryers, ignoring factors that can affect the performance results [13, 15]. Cay et al. [16, 17] investigated the performance parameters of dryers via exergy analysis and mathematical models and proposed a correlation between the dryer performance and the exergy efficiency. Sousa et al. [18] focused on the moisture distribution in textile sheets and discovered that moisture variations of the samples in a convective drying process occurred uniformly with respect to position and time.

Deans et al. [19] assessed the performance of heat-pump dryers and electric dryers according to the specific moisture extraction rate (SMER). The results indicated that heat-pump dryers have greater potential for energy saving than electric dryers. Yadav et al. [20] set an empirical correlation for the SMER to transfer energy consumption information among three standards: the Australian/New Zealand standard, the International Electrotechnical Commission standard and the American National Standards Institute standard. To et al. [21] compared the performance of electric dryers and gas dryers under the same $m_{BD}$. The study revealed that electric dryers have a lower SMER and that gas dryers are more ecofriendly and economical. Although numerous studies have been performed, the energy efficiency of electric dryers has hardly been improved. According to the definition of the SMER, the performance evaluation of dryers based on the drying rate and energy efficiency is not comprehensive enough [22].

As assessment indices, the aforementioned studies employed the moisture extraction rate (MER) and SMER. However, the indices differed among these studies; therefore, researchers can hardly apply the same indices in their works. Compared with electric dryers and heat-pump dryers, few studies on the performance of gas dryers have been conducted. Furthermore, there have been few investigations involving a comparison of the three types of clothes dryers.

The primary objective of this study was to assess the performance of the three types of clothes dryers according to five indices: the MER, SMER, specific thermal energy consumption for dehumidification ($m_{SPC}$), energy efficiency ($\eta_t$) and primary energy efficiency ($\eta_I$). These indices were defined according to the literature. An experiment was performed via the pretreatment dry method, which is defined in the Chinese national standard GB/T 20292-2006 [23].

2. EXPERIMENT AND METHODOLOGY

2.1. Description of dryers

The drying process of a gas dryer is shown in Figure 1. The dryer is composed of five parts: a bottom cabinet, a combustor, a hot-wind duct, a drum and an exhaust fan. A negative pressure in the gas dryer is produced by the exhaust fan, and the ambient air is drawn into the bottom cabinet because of the pressure difference. Part of the air from the bottom cabinet is drawn into the combustor via ejection as the primary air to premix with natural gas. The pressure difference causes secondary air to enter the combustor, providing gas with high thermal energy. Subsequently, the gas with high thermal energy is mixed with another part of the air from the bottom cabinet in the hot-wind duct. The gas is cooled to a temperature suitable for drying clothes. The mixed hot gas from the hot-wind duct is drawn into the drum. The drum continuously turns to from the clothes. The temperature and humidity of the exhaust gas increase. Finally, the humidified gas exits the dryer via the exhaust fan.

The drying process of an electric dryer is shown in Figure 2. The dryer is composed of four parts: a blast fan, a resistance wire, a drum and a moisture discharge duct. Unlike the drying process of gas dryers, the kinetic energy of the hot gas is generated by a blast fan, and heat energy is obtained from a resistance wire. The drying process in the drum of an electric dryer is similar to that.
of a gas dryer. Finally, the exhaust gas gains moisture from the clothes and is discharged via the moisture discharge duct.

The drying process of a heat-pump dryer is shown in Figure 3. It can be divided into two parts: a refrigeration cycle and a gas cycle. Similar to an air-conditioning system, the refrigeration cycle involves a compressor, a condenser, a capillary and an evaporator. R134a is used as the refrigerant in this heat-pump dryer. In the compressor, the vapor of the refrigerant is drawn into the suction side, and then the refrigerant is compressed to reach a suitable high pressure for condensing. The high-pressure vapor of the refrigerant discharged from the compressor flows through the condenser tubing and heats the gas with a low humidity and temperature. Simultaneously, the refrigerant is cooled until it is completely liquefied or sub-cooled. In the capillary, the flow control has a narrow opening, which results in large pressure loss when refrigerant flows through the capillary. Additionally, the refrigerant flows out of the capillary as a saturated liquid–vapor mixture. The refrigerant flows through evaporator tubing, which is heated by the gas blown from a recirculating fan. Then, the gas is cooled and moisture is extracted from the humidified gas. Finally, the refrigerant generally flows out of the evaporator as either saturated vapor or superheated vapor and is then drawn into the compressor to start a new cycle.

The circulation pattern of the gas in the heat-pump dryer differs significantly from those in the gas dryer and electric dryer. The gas in the heat-pump dryer can be circulated. The ambient air is drawn into the duct via the pressure difference induced by the recirculating fan. To reach the saturated gas temperature, the gas flows through the evaporator and is cooled at a relative humidity of 90%. Simultaneously, moisture is extracted from the gas. Water condensed from the humidified gas is collected in a water container. The gas flowing through the evaporator and the water container is at a low humidity and temperature. Subsequently, the gas heated in the condenser is drawn into the clothes drum to extract moisture from the testing load, which results in a decrease in temperature and an increase in humidity. Finally, the gas is drawn into the recirculating fan to start a new cycle.

2.2. Performance parameters

In this study, the performance of the clothes dryers was evaluated using the following indices.

2.2.1. Moisture extraction rate

The MER refers to the mass of moisture extraction per unit time. The MER only considers the drying rate of the overall performance of the system.

\[
\text{MER} = \frac{m}{t}
\]

Here, \( m \) and \( t \) are the mass of moisture extraction and the test duration, respectively.

2.2.2. Specific moisture extraction rate

The SMER refers to the energy consumption of the dryer for removing moisture per unit mass [22]. It is the most important indicator for evaluating the performance of a dryer and can fully reflect the energy efficiency of the dryer.

\[
\text{SMER} = \frac{E_t}{m}
\]

Here, \( E_t \) is the energy consumption of the clothes dryer. The energy consumption of a gas dryer includes the energy input from the burner and the electrical power input to the burner fan, the main fan and the drum motor [7]. The energy consumption of an electric dryer includes the electrical power input to the wire resistance, the main fan and the drum motor. The energy consumption of a heat-pump dryer is divided into two parts: the compressor and the motor. The energy consumption of the motor includes the electricity that drives both the main fan and the drum.

2.2.3. Specific energy consumption for dehumidification (\( m_{\text{SPC}} \))

The specific energy consumption for dehumidification (\( m_{\text{SPC}} \)) refers to the mass of moisture removed per unit thermal energy.
consumed by the drying system. This index is directly proportional to the amount of removed moisture and inversely proportional to the energy consumption of the drying system. A larger $m_{SPC}$ indicates that the dryer can save more energy. $m_{SPC}$ reflects the energy efficiency of the drying system.

$$ m_{SPC} = \frac{m}{E_d} \tag{3} $$

Here, $E_d$ is the energy consumption of the drying system. The thermal energy consumption of a gas dryer includes thermal energy released by natural gas combustion. In electric dryers, the energy consumption of the drying system ($E_d$) refers to the electricity consumption of the wire resistance. In heat-pump dryers, $E_d$ refers to the electricity consumption of the compressor.

2.2.4. Energy efficiency ($\eta_1$)

The energy efficiency ($\eta_1$) refers to the ratio between the energy consumption of the dryer for removing moisture and the total energy consumption of the dryer. This indicator reflects the energy efficiency of the dryer.

$$ \eta_1 = \frac{mr_w}{3600E_i} \tag{4} $$

Here, $r_w$ is the latent heat of vaporization in water.

2.2.5. Primary energy efficiency ($\eta_1$)

The primary energy efficiency ($\eta_1$) refers to the ratio of the energy consumption for removing moisture to the primary energy consumption ($\eta_1$). It is an important indicator reflecting the energy efficiency of the dryer and is relevant to the utilization of energy, e.g., coal, natural gas and petroleum. In China, the efficiency of the fossil-fuel power station is $\sim$41%. Therefore, the consumed electricity is converted into $\eta_1$ according to the ratio of 41%.

$$ \eta_1 = \frac{mr_w}{3600\left(\frac{E_i}{sA} + Q_g\right)} \tag{5} $$

Here, $Q_g$ is the heat input of the gas dryer when the temperature of the natural gas is 15°C.

2.3. Experimental methods

The performance of three types of domestic clothes dryers was analysed according to the pretreatment drying method. The experimental conditions were as follows:

1. The ambient temperature was 20°C, and the dry mass of the testing load was 1.5, 2.5, 3.5 and 4.5, and 6 kg.
2. The dry mass of the testing load was 3.5 kg, and the ambient temperature was 5, 7.5, 10, 12.5, 15 and 20°C.

### Table 1. Main parameters of experimental clothes dryers.

| Type of dryer   | Gas dryer | Heat-pump dryer | Electric dryer |
|----------------|-----------|-----------------|---------------|
| Rated drying capacity (kg) | 6         | 8               | 6             |
| Rated gas input (kW) | 4         | —               | —             |
| Rated power (W) | 260       | 650             | 2000          |
| Motor rated power (W) | 260       | 195             | 165           |

### Table 2. Components of natural gas in Chongqing.

| Component          | Value          |
|--------------------|----------------|
| Methane (vol. %)   | 96.2136        |
| Ethane (vol. %)    | 0.635          |
| Propane (vol. %)   | 0.073          |
| Carbon monoxide (vol. %) | 3.7     |
| Oxygen (vol. %)    | 0.0015         |
| Nitrogen (vol. %)  | 1.4            |
| Net calorific value (MJ/m³) | 35.04 |

2.3.1. Objective and materials

In this study, the heat required for the three dryers to heat the air came from natural gas combustion, circulation in the heat pump and the heating wire. The main parameters of the selected clothes dryers are presented in Table 1. The electric dryer and gas dryer used in this study both had a rated drying capacity of 6 kg. Because a heat-pump dryer with a rated drying capacity of 6 kg could not be found on the Chinese market, a heat-pump dryer with a rated drying capacity of 8 kg were selected. Rated power refers to the rated electric consumption of clothes dryer. The motor rated power includes the rated electrical power input to the motor and the fan of the clothes dryer, rather than the rated electric power to heating devices.

In contrast to the gas dryer, the electric dryer and heat-pump dryer only had one operating mode. The gas dryer had two modes: mode 1 and mode 2. Under the optimum working conditions, the natural gas consumption of modes 1 and 2 was 0.057 and 0.051 m³/kg, respectively. Owing to the higher natural-gas flow, mode 1 had a higher drying power than mode 2, resulting in a different temperature and humidity of the dried hot gas drawn into the drum. Therefore, the drying rate of mode 1 was higher than that of mode 2. A gas flow meter and an electricity meter were used to measure the consumption of gas and the electricity in the dryers, respectively. A temperature-and-humidity recorder and a U-type manometer were used to measure the temperature and humidity of the air and the pressure of the gas at the inlet of the dryer, respectively.

When the temperature and pressure of natural gas are 15°C and 2000 Pa, respectively, the net calorific natural gas in Chongqing can be calculated according to the components of the natural gas (Table 2).
2.3.2. Experimental procedure

Unless the testing load reached a stable state with the ambient atmosphere, the moisture exchange between the load and environment was continued. At equilibrium, the moisture content of the testing load was affected by the ambient temperature and relative humidity. Because of the complex exchange process of moisture and different experimental conditions, a proper method had to be selected to ensure that the testing loads were under the same drying mass. In this study, we selected the pretreatment drying method to obtain the same dry mass. This method is presented in appendix C and is based on the Chinese national standard GB/T 20292-2006. It defines the process and the basic rules of the pretreatment drying method [23].

When the testing load is treated according to the pretreatment drying method, it should satisfy the following rules. First, the ratio of the dry mass of clothes to the volume of the dryer should be >0.05 kg/L. In the gas dryer, the diameter of the drum was 59.5 cm, the depth was 37 cm and the volume was 102 L. According to the aforementioned ratio, the dry mass of clothes in the gas dryer should not be >5 kg. When the dry mass of clothes reaches the maximum value of 6 kg, it should be divided into 3.5 and 2.5 kg to perform the experiment. Second, the heating power of the clothes dryer used in the pretreatment drying method should be <3.3 times the rated power of the dryers used in the performance-assessment experiment [23]. In the pretreatment drying method, the load used in the experiment of the gas dryer and the electric dryer can be dried under mode 1 of the heat pump dryer. The experimental test was divided into two parts. In the first part, the initial moisture and final moisture of the tester clothes dryers (mBD) were recorded again. Additionally, the mass of the testing load after dehydration was referred to as the mass of the testing load before drying (m0).

The drying process of the pretreatment drying method lasted for 30 min. To ensure that the experiment was not influenced by intertwining clothes, the testing load was stirred manually every 10 min. The time consumption in the stirring process was controlled within 30 s. After 30 min of the drying process, we measured the weight of the load immediately. The weight can be recorded as the dry mass of the load (mBD), provided that the mass difference between the dried load and the load before drying is <1%. Therefore, the initial moisture and final moisture of the testing load were determined according to 1.06 mBD.

The initial moisture of the testing load (X0) refers to the moisture content without drying after dehydration. The final moisture of the testing load (Xf) was defined as the moisture content of the load after drying that satisfies the drying requirement. In this study, we selected 60% as the standard initial moisture. If X0 > 60%, the clothes should be placed in the dryer to remove moisture again until X0 decreases to 60%. In contrast, when the initial moisture is <60%, a spraying agent must be used to increase X0. X0 should be controlled at 60%; therefore, the dry mass of clothes can be calculated. X0 can be calculated as follows:

\[
X_0 = \frac{m_0 - 1.06m_{BD}}{1.06m_{BD}},
\]  

where \(m_0\) and \(m_{BD}\) are the mass of the testing load before drying and the dry mass of the testing load, respectively. The final moisture of the testing load (Xf) must be tested at 0 ± 3%. It can be calculated as follows:

\[
X_f = \frac{m_f - 1.06m_{BD}}{1.06m_{BD}},
\]  

where \(m_f\) is the mass of the testing load after drying. When the dry mass of the testing load (mBD) is recorded, the performance test of the dryers can be conducted. In this study, the effects of the temperature and dry mass on the dryer performance were investigated. It has been demonstrated that in equilibrium, the moisture content of fabrics is related to the moisture content of the ambient air [24]. Because the ambient temperature and the relative humidity affect the experimental results, to ensure the accuracy of the experiment, a monitoring device for the ambient temperature and relative humidity was set 1 m ahead of the air inlet of the dryer. The experimental test was divided into two parts. In the first part, mBD was selected as the variable to assess the performance of the dryers. The ambient temperature and the relative humidity were controlled at 20 ± 2°C and 55 ± 5%, respectively. The performance of the dryers was assessed at the following dry masses of clothes: 1.5, 2.5, 3.5, 4.5 and 6 kg. In the second part, mBD and the relative humidity were controlled at 3.5 kg and 55 ± 5%, respectively. The performance of the gas dryer and the electric dryer were assessed at ambient temperatures of 5, 7.5, 10, 12.5, 15 and 20°C. To ensure the accuracy of the results, the experiment was performed twice under each condition. Then, the average of the results was taken as the final experimental data.

The operating procedure is summarized as follows:

(1) The fluctuations of the ambient temperature and the relative humidity were monitored within ±1°C and 55 ± 5%, respectively, which satisfies the experimental requirements of the Chinese national standard GB/T 20292-2006.

(2) Different masses of clothes were selected for the experiment.

(3) The pretreatment drying method was used to ascertain the dry mass of clothes in the experiment. The testing load was dried in the dryers until the final moisture content was 3%. This operation was repeated five times.

(4) The electric dryer was placed in a washer for washing and dehydration, to reach 60% of the initial moisture of the load (X0). The mass of the load after dehydration was referred to as the mass of the testing load before drying (m0).

(5) Before each test, the hair filter was cleaned and the instruments were zeroed and calibrated. When the test began, the time was recorded.

(6) When the drying process was complete, the time was recorded again. Additionally, the mass of the testing load after drying (m1), the electric consumption of the different clothes dryers (E), the gas consumed by the gas dryer (Vg), the total electric consumption of the electric dryer...
The cleaning of the hair filter has a significant impact on the performance of dryers. The flow of hot gas in the dryers can be significantly affected by a blocked hair filter.}

3. RESULTS AND DISCUSSION

3.1. Effect of dry mass of clothes \((m_{BD})\) on performance of domestic clothes dryers

In first part of the experiment, the pressure was set below 2000 Pa at a natural-gas temperature of 15 \(^\circ\)C. The relative humidity and the temperature of the ambient air were controlled at 60\% and 20\(^\circ\)C, respectively.

3.1.1. Moisture extraction rate

Figure 4 presents the variation of the MER with respect to the dry mass of clothes. As shown, the variable regularity of the MER in the two modes of the gas dryer was similar to that for the electric dryer. Consider mode 2 as an example for analysis. With an increase of the dry mass from 0.5 to 6 kg, the MER increased from 1.34 kg/h and reached the highest level of 1.87 kg/h at 4.5 kg. It then decreased from 1.87 to 1.81 kg/h at 6 kg. When \(m_{BD}\) was < 4.5 kg, the effective contact area between the testing load and the hot gas increased with \(m_{BD}\). Meanwhile, owing to the increase of the resistance, the heat exchange and mass transfer increased; thus, the MER increased. If \(m_{BD}\) was greater than 4.5 kg, the intertwining and stacking of the testing load were less dispersed, resulting in a lower dehumidification efficiency and a smaller contact area. However, compared with the other dryers, the MER of the heat-pump dryer continuously increased when \(m_{BD}\) increased from 0.5 to 6 kg. When the dry mass was 6 kg, the heat-pump dryer could not reach the rated capacity of 8 kg. Nevertheless, when \(m_{BD}\) reached 6 kg, both the gas dryer and the electric dryer were below the rated drying capacity.

Comparing the MERs of the three types of clothes dryers revealed that mode 1 of the gas dryer had the highest MER. When the dry mass of clothes was 3.5 kg, the MER of the gas dryer reached the highest value of 3.01 kg/h. The MER of model 1 was 1.57–1.90 times that of model 2, 1.93–2.22 times that of the electric dryer and 2.11–3.14 times that of the heat-pump dryer. To measure the temperature at the inlet of the drum, a thermocouple was used. After the measurement, the temperatures of models 1 and 2 reached 200 and 100 \(^\circ\)C, respectively, whereas those of the electric dryer and heat-pump dryer reached 60–80 \(^\circ\)C and 50–55 \(^\circ\)C, respectively. These results confirm the aforementioned regularity. It is suggested that the gas clothes dryer had the highest MER. Models 1 and 2 of the gas dryer, the electric dryer, and the heat-pump dryer reached the optimum MER when the dry mass of clothes was 3–4 kg, 4–5 kg, 4–5 kg and 6–8 kg, respectively.

3.1.2. Specific moisture extraction rate

Figure 5 shows the variation of the SMER with the increasing dry mass of clothes. The variable regularity of the SMER for the two modes of the gas dryer was similar to that for the electric dryer. Here, we take model 2 of the gas dryer as an example for analysis. When the dry mass of clothes \((m_{BD})\) increased from 0.5 to 6 kg, the SMER decreased to 1.22 kW·h/kg at 4.5 kg and then increased to 1.24 kW·h/kg at 6 kg. With the increase of the resistance and contact area of the testing load, the time of heat exchange and the ability of mass transfer between the hot gas and the testing load increased when \(m_{BD}\) was < 4.5 kg. When \(m_{BD}\) was > 4.5 kg, the intertwining and stacking of the testing load was less dispersed, resulting in a smaller contact area and a higher SMER. However,
the SMER of the heat-pump dryers gradually decreased when \( m_{\text{BD}} \) increased from 0.5 to 6 kg. The reason for this phenomenon is similar to the reason mentioned for the MER.

The heat-pump dryer had the lowest SMER among the three types of dryers. When \( m_{\text{BD}} \) was <2.5 kg, the electric dryer had the lowest SMER and model 2 of the gas dryer had a lower SMER than model 1. When \( m_{\text{BD}} \) was >3.5 kg, the SMER of the electric dryer was approximately equal to that of the gas dryer. The heat-pump dryer reached the minimum SMER at the dry mass of 6 kg, whereas the other types of dryers reached the minimum SMER at 4.5 kg. The maximum SMER decreased in the following order: model 1 of the gas dryer, the electric dryer, model 2 of the gas dryer and the heat-pump dryer. The minimum SMERs for these dryers were 1.29, 1.26, 1.23 and 0.041 kW·h/kg, respectively. The two models of the gas dryer and the electric dryer reached the optimum SMER when \( m_{\text{BD}} \) was 4–5 kg. The heat-pump dryer reached the highest SMER when \( m_{\text{BD}} \) was 6–8 kg.

3.1.3. Thermal energy consumption for dehumidification

Figure 6 shows the variation of the specific thermal energy consumption (\( m_{\text{SPC}} \)) with the increasing dry mass. In Figure 6, the \( m_{\text{SPC}} \) values for the gas dryer and the electric dryer exhibit similar patterns: they increased from 0.7 kg/(kW·h) at 1.5 kg to 1.0 kg/(kW·h) at 3.5 kg. However, the \( m_{\text{SPC}} \) of the heat-pump dryer increased with \( m_{\text{BD}} \). This is because the heat-pump dryer could not reach the rated drying capacity when \( m_{\text{BD}} \) was 6 kg. At the same \( m_{\text{BD}} \), the heat-pump dryer had the highest \( m_{\text{SPC}} \) among the three types of dryers. The \( m_{\text{SPC}} \) of model 2 of the gas dryer was approximately equal to that of the electric dryer and was higher than that of model 1. The reason for the variation of \( m_{\text{SPC}} \) is described as follows.

The dryer had a device monitoring the heat and humidity in the drum, as the natural-gas flow varied with respect to the load. Greater gas flow led to a higher temperature of the hot gas flow at the entrance of the drum. Tests revealed that the average temperature of the hot gas flow at the entrance of the drum was 200°C. As described in 2.1, the hot gas in a gas dryer does not circulate. Consequently, the gas with high thermal energy cannot be exchanged properly with the testing load and is quickly discharged by the fan. Much of the thermal energy in the hot air is wasted, and the utility efficiency is low. However, both model 2 of the gas dryer and the electric dryer had a lower thermal energy and flow rate than model 1. Therefore, the thermal energy of the hot gas wasted in the drying process was lower.

When \( m_{\text{BD}} \) was 4.5 kg, the \( m_{\text{SPC}} \) of the electric dryer, model 2 of the gas dryer, and model 1 were optimized. In accordance with the foregoing analysis, the heat-pump dryer reached the highest \( m_{\text{SPC}} \) when \( m_{\text{BD}} \) was 6–8 kg. The maximum \( m_{\text{SPC}} \) values for the heat-pump dryer, model 2, the electric dryer and model 1 were 3.772, 0.9134, 0.8724 and 0.8314 kg/(kW·h), respectively.

3.1.4. Energy efficiency

Figure 7 shows the variation of the energy efficiency (\( \eta_t \)) with respect to the dry mass of clothes. The \( \eta_t \) of the gas dryer and the electric dryer first increased from the lowest level (1.5 kg) to the peak value (4.5 kg) and then decreased by \( \sim 50\% \) at 6 kg. The \( \eta_t \) of the heat-pump dryer increased with the increase of \( m_{\text{BD}} \) from 1.5 to 6 kg. The reason for this regularity was the reason mentioned previously. At the same \( m_{\text{BD}} \), the \( \eta_t \) of the heat-pump dryer was significantly higher than those of the gas dryer and the electric dryer. The electric dryer and modes 1 and 2 of the gas dryer had the highest \( \eta_t \) when \( m_{\text{BD}} \) was 4.5 kg: 55.85%, 54.51%, and 53.11%, respectively. The heat-pump dryer had the optimum energy efficiency of 166.84% when \( m_{\text{BD}} \) was 6 kg.

3.1.5. Primary energy efficiency (\( \eta_1 \))

Figure 8 shows that the primary energy efficiency (\( \eta_1 \)) increased with the dry mass of the load (\( m_{\text{BD}} \)). The \( \eta_1 \) of the gas dryer and the electric dryer first increased from approximately 34% at 1.5 kg to the highest value of 48% at 4.5 kg and then decreased to 45%.
at 6 kg. However, the efficiency of the heat-pump dryer increased with the increase of $m_{BD}$ from 1.5 to 6 kg. As shown in the figure, at the same $m_{BD}$, the $\eta_1$ of the heat-pump dryer was significantly higher than those of the gas dryer and the electric dryer. The heat-pump dryer had the optimum primary efficiency at the dry mass of 6 kg. The $\eta_1$ of model 1 of the gas dryer was approximately equal to that of model 2 at the same point (∼45%). When $m_{BD}$ was 4.5 kg, the electric dryer, model 2 and model 1 exhibited the highest $\eta_1$: 48.43%, 48.39% and 22.35%, respectively. The heat-pump dryer exhibited the highest $\eta_1$ at the dry mass of 6 kg.

3.2. Effect of ambient temperature on performance of domestic clothes dryers

When the dry mass of the testing load ($m_{BD}$) was 3.5 kg, the pressure of the natural gas in the experiment was < 2000 Pa. The relative humidity reached 60%, and the temperature of the natural gas reached 20℃. Compared with the case of the temperature of 20℃, the performance of the heat-pump dryer at 30℃ was only slightly improved and could be predicted easily. Similarly, the performance of the gas dryer and the electric dryer at the ambient temperature of 30℃ was only slightly better than that at 20℃. No further experiments were conducted.

3.2.1. Moisture extraction rate

Figure 9 shows the relationship between the MER and the ambient temperature. The MERs of the three types of clothes dryers increased with the temperature of the ambient air. With the increase of the ambient temperature, the temperature of the hot gas increased, yielding a higher MER. However, the heat-pump dryer was more sensitive to the temperature than the other types of dryers. The MER of the heat-pump dryer reached 0.57 and 1.02 kg/h at the ambient temperatures of 5 and 20℃, respectively. This is because the drying process of the heat-pump dryer can be divided into a hot-gas cycle and a refrigeration cycle. At a lower ambient temperature, frost was easily accumulated on the surface of the evaporator, and the heat-exchange efficiency of the evaporator and the MER of the heat-pump dryer decreased. Compared with the electric dryer and gas dryer, the heat-pump dryer was greatly affected by changes in the ambient temperature. However, the hot gas in the gas dryer gained thermal energy from the natural gas, whereas the hot gas in the electric dryer gained thermal energy from the electric energy. Additionally, in the electricity dryer, the ambient temperature had little impact on the performance of the heating device. Therefore, the ambient temperature had little influence on the MERs of the electric dryer and gas dryer.

When the ambient temperature was between 5 and 7.5℃, the MER was minimized owing to the accumulation of frost. With the increase of the ambient temperature, the heat-pump dryer gradually reached normal operating conditions. The MER of the heat-pump dryer at 20℃ was 2 times that at 5℃. At the same
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ambient temperature, the MER decreased in the following order: model 1 of the gas dryer, model 2, the electric dryer, and the heat-pump dryer. The MER of model 1 was 1.88–1.97 times that of model 2, 2.56–2.96 times that of the electric dryer, and 3.32–5.8 times that of the heat-pump dryer.

3.2.2. Specific moisture extraction rate

Figure 10 shows the variation of the SMER with the increase of the ambient temperature. Clearly, the SMERs of the three types of clothes dryers decreased with the increase of the ambient temperature. The ambient temperature had little effect on the performance of the gas dryer. However, the SMERs of the electric dryer and heat-pump dryer exhibited far larger changes. The hot gas in the gas dryer gained thermal energy from the combustion of natural gas. Therefore, the ambient temperature had little influence on the performance of the gas dryer. When the temperature was low, the electric dryer required more electric energy to maintain a high temperature. Furthermore, the flow velocity of air and thermal energy decreased because of the accumulation of frost on the evaporator. Compared with the electric dryer, the ambient temperature had a greater impact on the performance of the heat-pump dryer. The SMER of the heat-pump dryer was more sensitive to the temperature than that of the electric dryer, although it exhibited a smaller slope from 15 to 20°C.

At the same ambient temperature, the SMERs of the four types of dryers decreased in the following order: the heat-pump dryer, model 2 of the gas dryer, model 1 and the electric dryer. Through the compressor, the heat-pump dryer can absorb heat from a low-temperature environment, heating the recycled gas in the dryer. Thus, the SMER of the heat-pump dryer was significantly lower than those of the electric dryer and gas dryer. Additionally, the exhaust gas discharged by the gas dryer had a large amount of available thermal energy. The temperature of the exhaust gas in model 1 (200°C) was higher than that in model 2 (120°C). The wasted thermal energy of model 2 was greater than that of model 1. Thus, the SMER of model 1 was higher than that of model 2. The SMER of the electric dryer was approximately equal to that of the gas dryer at the ambient temperature of 20°C. The SMER of the heat-pump dryer was 0.39–0.58 times that of model 1, 0.30–0.61 times that of model 2, and 0.38–0.46 times that of the electric dryer. According to the foregoing analysis, the heat-pump dryer exhibited the best energy-saving performance.

3.2.3. Specific thermal energy consumption for dehumidification (m_{SPC})

Figure 11 shows the variation of the specific thermal energy consumption for dehumidification (m_{SPC}) with the increase of the ambient temperature. The m_{SPC} of the three types of clothes dryers increased with the ambient temperature. Compared with the other dryers, the m_{SPC} of the heat-pump dryer was far more
sensitive to the ambient temperature. At the same ambient temperature, the $n_{SPC}$ of the heat-pump dryer was significantly larger than those of the electric dryer and the gas dryer, and the $n_{SPC}$ of model 2 of the gas dryer was slightly larger than that of model 1. The $n_{SPC}$ of the heat-pump dryer was 2.7–3.77 times that of model 1, 2.45–3.56 times that of model 2 and 3.27–4.0 times that of the electric dryer. According to the foregoing analysis, the heat-pump dryer had the best energy-saving performance. The heat-pump dryer had steady energy efficiency in the ambient-temperature range of 15–20°C.

3.2.4. Energy efficiency ($\eta_1$)
Figure 12 shows the variation of the energy efficiency ($\eta_1$) with respect to the ambient temperature. Similar to the $m_{SPC}$, at the same ambient temperature, the $\eta_1$ of the heat-pump dryer was significantly higher than those of the electric dryer and the gas dryer. The $\eta_1$ of model 2 of the gas dryer was slightly higher than that of model 1. The $\eta_1$ of the heat-pump dryer was 1.73–2.57 times that of model 1, 1.64–2.51 times that of model 2, and 2.15–2.68 times that of the electric dryer. According to the foregoing analysis, the heat-pump dryer had the best energy-saving performance.

3.2.5. Primary energy efficiency ($\eta_1$)
Figure 13 shows the variation of the primary energy efficiency ($\eta_1$) with the increase of the ambient temperature. The $\eta_1$ of all three types of dryers increased with the ambient temperature. However, the ambient temperature had little impact on the $\eta_1$ of the gas dryer. The $\eta_1$ values of the heat-pump dryer and the electric dryer were significantly more sensitive to the ambient temperature, particularly that of the heat-pump dryer. Because the time of drying for model 2 of the gas dryer was longer than that for model 1, model 2 consumed far more electric energy than model 1. At the same ambient temperature, the $\eta_1$ of model 1 was slightly higher than that of model 2. Natural gas is a primary energy source. Consequently, when the ambient temperature was < 9.5°C, $\eta_1$ decreased in the following order: model 1, model 2, the heat-pump dryer, and the electric dryer. When the ambient temperature was > 10.5°C, the $\eta_1$ of the heat-pump dryer was higher than those of the gas dryer and the electric dryer. With the increase of the ambient temperature, the advantage of the heat-pump dryer with regard to $\eta_1$ became more obvious.

4. CONCLUSION
The performance of three types of clothes dryers was assessed under different ambient temperatures and dry masses of the testing load ($m_{BD}$), in order to evaluate the effects of the temperature and the dry mass on the MER and energy efficiency ($\eta_1$) of the dryers. According to the results, the following conclusions are drawn:

1. When $m_{BD}$ increased from 1.5 to 6 kg, the MERs of the gas dryer and the electric dryer first increased and then decreased. In contrast, the MER of the heat-pump dryer constantly increased with $m_{BD}$. Among the three types of dryers, the gas dryer and heat-pump dryer had the highest and lowest MERs, respectively.
2. Similar to the MER, with the increase of $m_{BD}$ from 1.5 to 6 kg, the $\eta_1$ of the gas dryer and the electric dryer first increased to the highest level and then decreased to the lowest level. At the same $m_{BD}$, the $\eta_1$ of the heat-pump dryer was higher than those of the other dryers, provided that the ambient temperature was > 10.5°C. The heat-pump dryer had a lower $\eta_1$ than the gas dryer when the ambient temperature was < 9.5°C. A higher ambient temperature yielded a higher $\eta_1$ of the heat-pump dryer.
3. The optimum performance was achieved when the dry mass was 3.5–4.5 kg, 4.5–5 kg, and 6–8 kg for the gas dryer, electric dryer and heat-pump dryer, respectively.
4. In cases where a high MER is needed, the gas dryer is the most suitable dryer for ordinary families. The MER and the $\eta_1$ of the three clothes dryers increased with the ambient temperature. Moreover, the heat-pump dryer was the most sensitive to the ambient temperature.

CONFLICTS OF INTEREST
The authors declare no conflict of interest.

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