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RAPID COMMUNICATION

Drying performance of a dishwasher with internal air circulation

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Abstract−This paper presents an experimental study on the energy flow and drying performance of a dishwasher with internal air circulation. A simple energy flow process was established to determine the energy consumption of a dishwasher with internal air circulation. The drying performance of the dishwasher was determined by evaluating dish wetness. The effect of various performance variables (e.g., final rinse temperature, air circulation flow rate, and fan operation time) on the drying performance and the energy consumption was assessed individually. All tests were performed following a slightly modified EN50242. The energy accumulated in the final rinse step was responsible for evaporating water off dishes. The drying performance increased as the energy consumption increased. More than 1.17 kWh energy was consumed to obtain a drying performance greater than 1.8.

Keywords: Drying, Dishwasher, Energy, Circulation

INTRODUCTION

With the increasing interest in energy-efficient appliances, various methods for improving dishwasher energy efficiency have been studied [1]. Paepe et al. [2] studied a dishwasher heat recovery system that used a heat exchanger. Lin et al. [3] simulated the operating conditions of a heat pipe heat recovery system. Persson [4] developed a dishwasher recovery system using a hot water circulation loop as a heat exchanger. These methods explored the ability to recover energy contained in wastewater, since a significant amount of energy is used to heat dishwasher water. It is difficult to apply these methods in compact appliances, and their energy savings are difficult to characterize. Compared to studies focused on improving dishwasher energy efficiency, studies on drying performance are rare.

Therefore, the objective of this study was to estimate energy flow at each step, and to investigate the effects of the final rinse temperature, circulation flow rate, and fan operation time on the drying performance in a dishwasher system with internal circulation of air, and to identify the relationship between the drying performance and energy consumption. All tests were performed following a slightly modified version of EN50242 for dishwashers.

EXPERIMENTAL SETUP

To estimate the factors affecting dishwasher drying performance

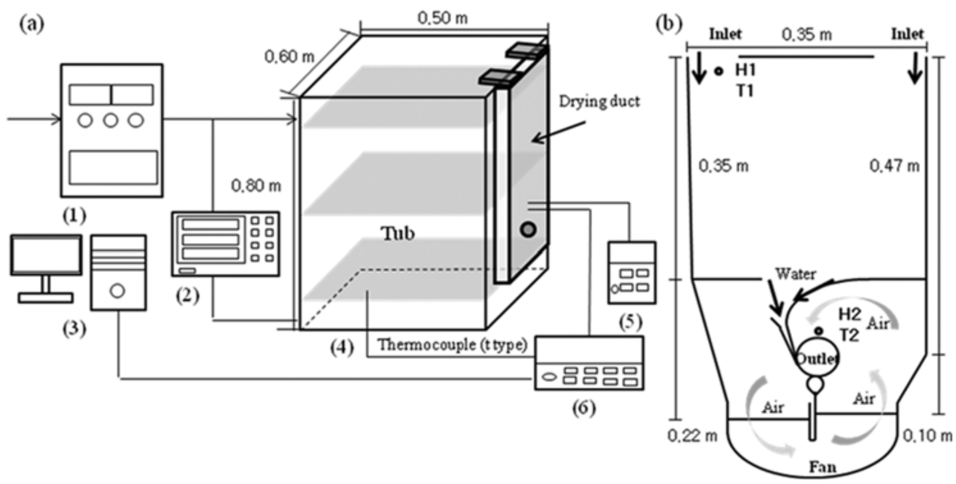

Fig. 1. Schematic diagram of (a) the dishwasher system, and (b) the drying duct (front view).
(1) Transformer (2) Power meter (3) Computer (4) Dishwasher (5) Datalogger-humidity (6) Datalogger-temperature

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Table 1. Experimental variables and ranges

Variable	Range
Final rinse temperature (°C)	55-70
Circulation gas flow rate ($\times 10^3$ m^3/s)	0.92-0.96
Fan operation time (s)	0-1800

Table 2. Criteria for estimating dish drying performance

Type (s) of observation	Score
Dry	2
Intermediate (A_w<55 mm^2)	1
Wet (A_w>55 mm^2)	0

and optimize operating conditions, a dishwasher system with internal air circulation was created, as shown in Fig. 1(a). The dishwasher mock-up was composed of a drying duct and tub where the dirty dishes were washed. Fig. 1(b) shows a front-view schematic diagram of the drying duct located on the right side of the tub. The surface close to the tub in the duct was composed of opaque acrylonitrile butadiene styrene (ABS), and the surface exposed to the atmosphere was composed of transparent polycarbonate (PC). The drying duct and tub were connected through two inlet points at the top of the drying duct, and one outlet point located 0.47 m below the inlet. A fan located at the bottom of the drying duct (0.57 m below the inlet point) caused the air-water vapor mixture to circulate by blowing humid air to the drying duct outlet point. The air circulation flow rate was changed from 0.92×10^{-3} m^3/s to 0.96×10^{-3} m^3/s by adjusting the fan voltage from 210 to 240 V, which was measured using an integrating flowmeter. Two thermocouples (T-type) installed in the drying chamber measured the temperature of the drying duct, and two humidity sensors measured the relative humidity inside the drying duct.

The operating variables were the final rinse temperature, air circulation flow rate, and fan operation time. The influence of each variable on the drying performance was investigated. The range of experimental variables is shown in Table 1.

The drying performance (P_d) was evaluated by scoring dish wetness.

The wet dish condition was determined by using the modified EN50242 (EUROPEAN STANDARD) [5]. As shown in Table 2, the wet condition was divided into three grades: *Dry*, *Intermediate*, and *Wet*. *Dry* was the state in which one or two droplets remained on the dish surface. *Intermediate* was the state in which more than two droplets or narrow streaks remained on the dish surface in a total wet area less than 55 mm^2. *Wet* was defined as the state in which more than two streaks remained on the dish surface, creating a total wet area larger than 55 mm^2. To represent the drying performance, 158 dishes per experimental condition were evaluated, and the average score was used.

RESULTS AND DISCUSSION

The energy balance was estimated to understand the flow of energy in this dishwasher system. Because there is no chemical reaction inside a dishwasher, the energy balance equation for this dishwasher system was expressed as follows:

$$\text{Energy accumulation}=\text{Energy input}-\text{Energy output} \tag{1}$$

The input energy, which refers to the electrical energy coming into the dishwasher system, was measured by a power meter. Incoming energy was converted to accumulation energy, which was the energy stored in the dishes, dishwasher, and water remaining inside the dishwasher. The accumulation energy, which could not be measured directly, was calculated as follows:

$$dq=m\cdot C_p\cdot dT \tag{2}$$

The dish temperatures and weights, dishwasher, and water remaining inside the dishwasher were measured by a thermocouple and balance. The specific heat of the water was 4.18 kJ/kg·°C. The dishwasher was composed of stainless steel and asphalt. The stainless steel and asphalt specific heats were 0.500 and 0.92 kJ/kg·°C, respectively. This study used three types of dishes: ceramic, stainless steel, and glass; their specific heats were 0.800, 0.500, and 0.748 kJ/kg·°C, respectively.

There are a variety of output energy forms, such as the energy included in the drainage, the energy emitted from the outer wall of the dishwasher to the atmosphere, and the outgoing energy in the form of water vapor. For drainage, the energy was calculated using Eq. (2) by measuring the temperature and weight. The energy emitted from the outer wall of the dishwasher to the atmosphere was assumed to occur in the form of natural convection, and was calculated using Eq. (3). The method for determining the value of h for natural convection is shown in detail in reference [6].

$$\frac{dq}{A}=h\Delta Tdt \tag{3}$$

where A is total outer dishwasher surface area, which was used as the heat transfer area.

The outgoing energy in the form of water vapor was calculated using the following procedure. The total weight of the dishwasher system, which varied throughout the cycle, was measured by placing the dishwasher on a scale [Mettler-Toledo, Model SR64001] at each operation point. The latent heat of the water, which was responsible for converting the water into water vapor, was calculated and corresponded to the variation in weight at each operating step, excluding drainage.

Fig. 2 shows the energy variation throughout the operating cycle in this dishwasher system. The energy balance was well adjusted until just before the drying step. However, the difference between the incoming energy, and the sum of the output and accumulated energies, increased throughout the drying step. Compared to the other steps, the drying step had two features: long duration and high temperature. As a result, the energy loss error for natural convection calculated in Eq. (3) increased during drying. The energy balance was investigated in detail by dividing the total energy into input, output, and accumulation energies. The input energy increased in the heating steps corresponding to the main wash and final rinse step. The output energy consistently increased throughout the operating cycle. The accumulation energy increased in the heating steps, and decreased in the non-heating steps. Based on these phenomena, the dishwasher system energy flow was inferred as follows. The accumulated energy in the system was converted to output en-

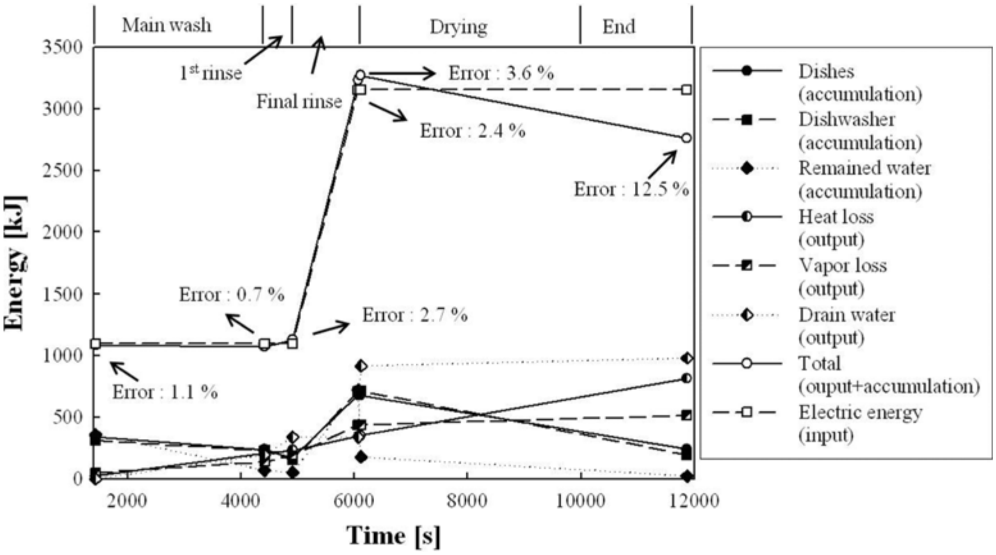

Fig. 2. Variation of energy in the dishwasher for each step.

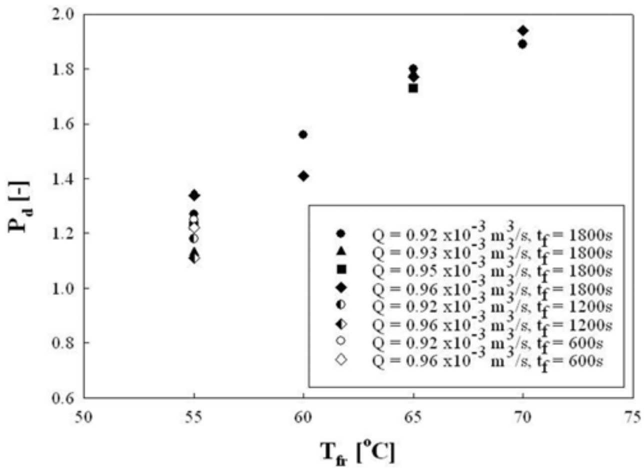

Fig. 3. Variation of drying performance with final rinse temperature (T_{fr}).

ergy, which was then released into the atmosphere. By estimating the energy balance, it was confirmed that the energy accumulated in the final rinse step was responsible for water evaporation from dish surfaces. Therefore, T_{fr} was an important factor in drying the dishes.

Fig. 3 shows the drying performance variation with T_{fr}. The drying performance tended to increase as the final rinse temperature increased. As shown in the energy balance results, the energy required to evaporate water from the dish surfaces during the drying step corresponded to the energy accumulated on the dishes from the heat energy supplied in the final rinse step. When the other conditions were the same, an increase in T_{fr} meant more energy was accumulated on the dishes, and therefore a larger amount of water evaporated from their surfaces.

In the dishwasher system, incoming energy was converted into thermal and mechanical energy. Therefore, the energy consumption was a function of the operating variables under the same con-

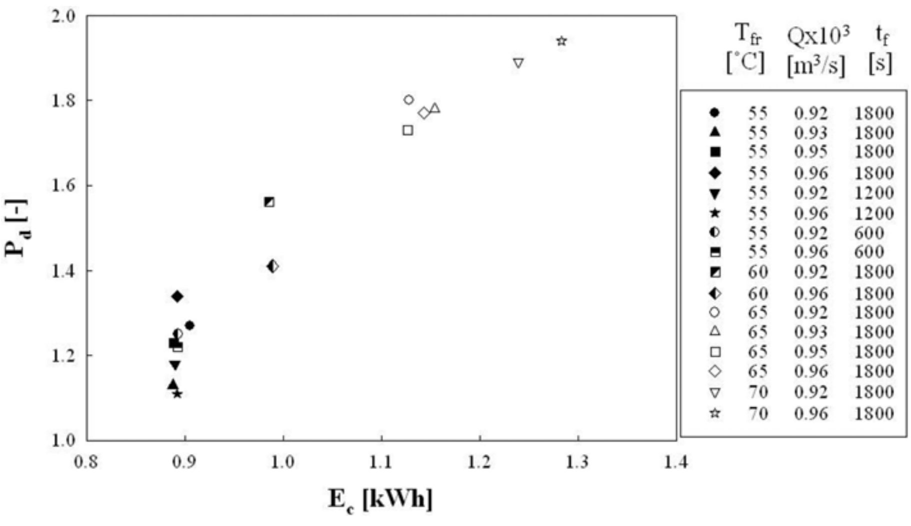

Fig. 4. Drying performance of dishes versus energy consumption of the dishwasher system.

ditions. Fig. 4 shows the relationship between energy consumption and drying performance. The drying performance improved as energy consumption increased. When the energy consumption was greater than 1.17 kWh, the drying performance was greater than 1.8, which is an acceptable value for this system. However, the relationship between energy consumption and drying performance in the low energy consumption area, which was less than 0.9 kWh, is not yet fully understood, and more detailed research is required.

CONCLUSIONS

We have presented experimental results on the drying performance of a dishwasher with internal air circulation. The study confirms that the energy accumulated in the final rinse step is responsible for evaporating water off dishes. Within the experimental operation range (T_{fr}=55-70 °C, Q=0.92-0.96×10^{-3} m^3/s, t_f=0-1800 s) with internal air circulation, the final rinse temperature was found to be the major factor affecting the drying performance and energy consumption. The performance data revealed that more than 1.17 kWh energy was consumed to obtain a drying performance greater than 1.8.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A : heat transfer area [m^2]
A_w : total wet area [mm^2]
C_p : specific heat [kJ/kg·°C]
E_c : energy consumption [kWh]
h : heat transfer coefficient [W/m^2·s]
P_d : drying performance [-]
q : heat energy [J]
Q : circulation flow rate [m^3/s]
T_{fr} : final rinse temperature [°C]
t : operating or measuring time [s]
t_f : fan operation time [s]
Y : absolute humidity [kg_v/kg_{DA}]

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