Energy Conversion and Management 157 (2018) 511–516

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Adaptive defrost methods for improving defrosting efficiency of household refrigerator

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ARTICLE INFO

Keywords:
Defrost
Heater
Refrigerator
Efficiency

ABSTRACT

The defrosting method of the conventional household refrigerator increases freezer temperature during the defrosting operation, and defrosting efficiency reduces because the heater consumes more power than the amount of frost on the surface of the heat exchanger. To solve this problem, three defrost heater control methods, applicable to refrigerators equipped with conduction and radiation heaters, are being proposed. The control methods were classified as a method of simultaneously pulsating two heaters, method of individually pulsating two heaters, and method of step-by-step reduction of radiation heater power. The operation effect of each heater on freezer temperature was analyzed. For the three methods, a heater control optimization process was performed to reduce the temperature increase in the freezer. The power consumed by the heater was minimized and defrosting efficiency improved. The Best performance was observed when two heaters pulsated individually. For this method, the variation in freezer temperature, between before and after the defrost process, was reduced from approximately 11 °C to 5 °C. Additionally, the defrosting efficiency improved by 15%.

1. Introduction

A refrigerator is continuously connected to the power supply to keep food fresh. Therefore, it is one of the household appliances with the largest energy consumption, in all households [1]. Since the evaporator in commercial refrigerators operates at a temperature below the dew point, moisture in the air condenses on the surface of the heat exchanger and forms a frost layer. This frost layer grows gradually as the operation time increases and acts as thermal and flow resistance [2], reducing the efficiency of the entire refrigeration cycle. Thus, a defrosting process is required to remove the frost layer. Currently, most defrost heaters used in household refrigerators include a sheathed heater using radiant heat and a distributed heater with conductive heat transfer. Such a defrost heater consumes significant power in order to generate high temperature during the defrosting process. Because of the high-temperature heater and the termination of the compressor, it is difficult to maintain the temperature of a refrigerator/freezer compartment. The excessive power consumption of defrost heaters deteriorates defrosting efficiency and the condition of the food in the freezer. This problem must be solved in terms of energy and product reliability.

Various frost detection and defrosting methods [3] have been studied in order to address the problem of the defrosting process. Kim et al. [4,5] proposed mass flow fraction method which is more accurate than the conventional time control defrost method, and in the louvered fin heat exchanger, an asymmetric louvered fin was applied to reduce the surface tension by about 11% compared with a symmetrical louvered fin, improving the drainage after defrosting. Ye et al. [6] studied a frost-delaying method in order to prevent the performance deterioration of the heat exchanger. Neither study addressed the thermal properties during the defrosting process. Bansal et al. [7] analyzed the ratio of heat storage from the defrost heater to the surrounding structure. Knabben et al. [8] calculated the ideal heat required for defrosting, according to each evaporator row, by observing the frost distribution; they found that the top part of the evaporator needed more heat energy than the bottom part. Ozkan et al. [9] proposed a model by which defrosting time was predicted according to the power of the defrost heater in a fin-tube heat exchanger. However, this method was not ideal for systems combining radiative and conductive defrost heaters. Ghadiri et al. [10] divided the defrost process into four stages and studied the power consumption at each stage. Liu et al. [11] reduced about 70% of the power consumption of a defrost heater using a heat storage system. Jhee et al. [12] studied the defrost behavior of fin-tube heat exchangers, and found that the residual water on the surface of the heat exchanger was affected only by the surface tension inherent to the heat exchanger and regardless of operating conditions. However, none of the above studies considered the effects of heat on the freezer's internal temperature. Mastrullo et al. [13] studied the effects of door opening,

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https://doi.org/10.1016/j.enconman.2017.12.039
Received 9 September 2017; Received in revised form 9 December 2017; Accepted 12 December 2017

Nomenclature

C_p	specific heat [kJ/kg·K]
E	energy [J]
h	latent heat [kJ/kg]
m	mass [g]
P	power [W]
T	temperature [°C]
t	time [min]

Greek symbols

ε	uncertainty [%]
η	efficiency [%]
τ	duration [s]

Subscripts

c	copper cylinder
d	defrost
dis	distributed heater
e	end
f	frost
h	heater
i	initial
id	ideal
m	melting/mass [g]
max	maximum
off	heater off
on	heater on
P	power [W]
T	temperature [°C]
sh	sheathed heater
sl	solid to liquid

and defrosting cycles, on freezer temperature. Gin et al. [14] and Ezan et al. [15] attempted to prevent an increase in freezer temperature by using a phase-change material in the freezer. Yu et al. [16] changed the air supply method in the vertical display refrigerator in order to reduce the temperature increase during defrosting. However, none of these methods achieved to stabilize the freezer temperature by controlling the defrost heater.

Dong et al. [17] improved defrosting efficiency by supplying a part of the heat, required for defrosting, from the indoor air, during the reverse cycle defrosting process of the air source heat pump. However, this is difficult to apply to the refrigerator, where the indoor air is maintained at approximately −18 °C. Melo et al. [18] improved defrosting efficiency by supplying power to a defrost heater in the form of pulses, instead of providing constant power. They supplied power in a step-by-step manner. However, since the pulse and stepwise power supply were applied based on a specific time, there was a problem by which the application was difficult, when the total defrosting time was lengthened or shortened according to the operating environment.

In this paper, three adaptive defrosting methods to control the heater by using the information of the temperature sensor, during the defrosting process of the household refrigerator, are proposed. The effects of the conduction heater, and radiation heater, on the increase in freezer temperature, were investigated. The optimized defrosting method diminished the increase in the freezer temperature and confirmed the energy saving effect by improving the defrosting efficiency.

2. Experiments

2.1. Experimental apparatus

Fig. 1 shows the heat exchanger of the freezing chamber (370 L) used in the experiment. R-600a (82 g) was used as a refrigerant. The installed defrost heaters included a sheathed heater (250 W) using radiant heat to dissolve the frost on the bottom of the evaporator and a distributed heater (85 W) to dissolve the frost on the upper portion of the evaporator through conductive heating. The two heaters were controlled using a defrost sensor (T_d) attached to the upper left side of the evaporator where the frost melts last. When the defrost sensor temperature reached 5 °C, the temperature of the evaporator tube on the top center was approximately 30 °C, indicating that all of the frost had melted, and therefore, the defrost cycle was terminated [19]. During the defrost process, a type-T thermocouple was installed to measure the variation in the freezer temperature, which was transferred to a data acquisition unit (NI 9213, cDAQ-9178).

In addition, an electronic scale (CB-6000, A & D) was used to measure the mass of the defrost water, and the heater power consumption was measured using a power meter (Clamp On Power HiTester, Hioki). Table 1 shows the measurement range, accuracy and uncertainty for each parameter. To investigate the increase in freezer temperature due to the heater, the air temperature of the top cabinet was divided into three parts (T_1, T_2, and T_3) during the defrost process as shown in Fig. 2.

Fig. 3 shows the variation of the air temperature in the top cabinet during the defrost cycle. The difference in the air temperature between the ceiling (T_1) and the floor (T_3) of the top cabinet could reach up to 17 °C. Therefore, it was not appropriate to use the air temperature as a measure of the increase in temperature. For this reason, an Association of Home Appliance Manufacturers (AHAM) standard copper cylinder with a diameter of 30 mm and a height of 30 mm was used to quantify the increase in temperature after the defrost cycle completed. A thermocouple was placed at the center of each copper cylinder installed at the center of each cabinet as shown in Fig. 2, to measure the temperature of the actual operating environment [20].

2.2. Experimental procedure

The experiments were conducted in accordance with ISO-15502 [21]. The ambient temperature and relative humidity were 25 ± 0.7 °C and 21 ± 1%, respectively. The freezer temperature was set to be maintained at −18 °C to make a general operating environment of household refrigerator (freezer). The mass of the frost was 220 ± 10 g. The greatest increase in temperature during the defrost cycle was observed in the top cabinet of the freezer; therefore, as shown in Fig. 4, the temperature variation observed before and after the defrost cycle of the top cabinet copper cylinder was investigated. The defrost process mentioned in the study of Ghadiri et al. [10] was applied to operate in a

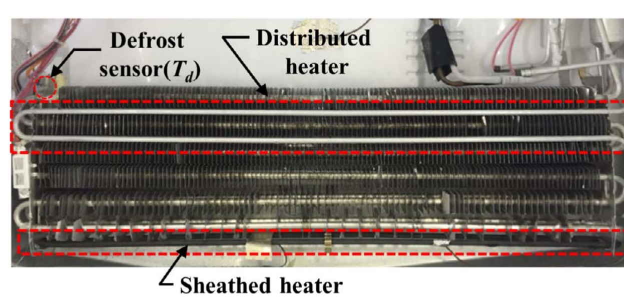

Fig. 1. Defrost heater and attachment position of the defrost sensor.