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Research Paper

A study on optimizing the energy consumption of a cold storage cabinet

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HIGHLIGHTS

- Energy efficiency of household refrigerators is investigated.
- The investigated parameters are airflow rate and evaporator temperature.
- Experiments are carried out and a simple computational model is built.
- Heat gain calculations of the refrigerator cabinet are also included in the model.
- The model outputs are validated by the experiment results.

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ABSTRACT

Refrigerators are cold storage cabinets used to store food. Run time ratio is an important factor contributing to the refrigerator energy consumption. An experimental study is presented, in which the parameters affecting the run time ratio of the freezer compartment of a "no-frost" household refrigerator is taken into account. Evaporator temperature and air flow rate are chosen as investigated parameters. The experiments are conducted in a setup where these parameters can be controlled. The freezer compartment is loaded with test packages according to the relevant refrigerator energy consumption testing standard. A simple mathematical model is built by which the run time ratio of a freezer compartment can be calculated according to other input parameters (such as insulation, and volume). The total energy consumption of a two-door refrigerator having fresh food storage and freezer compartments can also be calculated using this mathematical model. The compressor and fan power consumption data are used to estimate energy consumption using the run time ratio. The experimental results are compared with the results obtained from the mathematical model for validation. The effects of the chosen parameters on the refrigerator total energy consumption are presented.

1. Introduction

Energy efficiency has been an important issue as the depletion of resources and global warming are coming up to critical levels. An important portion of electricity consumption is comprised of household consumption. Refrigerators and freezers are seen to be major contributors to household electricity consumption by a ratio of 14–19% [1]. Therefore it can be concluded that an improvement in the energy efficiency of household refrigerators can result in considerable amounts of energy saving. It is estimated that an energy saving up to 6 TWh per year can be obtained by the year 2020, if ecological design and energy labeling policies are implemented successfully [2].

Refrigeration system optimization is an important asset in reducing energy consumption of a refrigerator by improving efficiency. Various parameters existing in a refrigeration system such as heat exchanger dimensions and flow rates of fluids can be chosen during the design of the refrigeration unit. In order to improve energy efficiency the parameters should be chosen correctly. Some of these parameters can be modified easily without causing a significant difference in product cost or production process of the refrigerator.

2. Literature research

Various studies have been conducted to interpret the refrigeration system in a household refrigerator. Some experimental studies have been conducted to assess the effect of system parameters on cooling performance. Also, some other studies focus on predicting

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Nomenclature

3D	3-dimensional	Q_e	cooling capacity
A	area	Q_t	thermal load
COP	coefficient of performance	ΔT_{lm}	logarithmic mean temperature difference
c_p	specific heat	Re	Reynolds number
d	tube diameter	rpm	revolutions per minute
DC	direct current	RT	runtime ratio
EC	energy consumption	RTD	resistance temperature detector
f	friction factor	T	temperature
G	mass flux	U	overall heat transfer coefficient
j	Colburn-j factor	V	voltage
$\dot{m}$	mass flow rate	$\dot{\mathbf{V}}$	air flow rate
N	number of fins	W	power
PIV	particle image velocimetry	ε	finning factor
PLC	programmable logic control	μ	viscosity
$\dot{Q}$	heat transfer rate	τ	runtime ratio

the energy consumption of refrigerators using either theoretical or semi-empirical approaches.

One of the most important components of a no-frost refrigeration system is the evaporator. Finned-tube type evaporators are widely used in no-frost refrigerators. It is, hence, critical to predict the performance of such evaporators for determining the performance of a refrigeration system. Karatas et al. [3] and Barbosa et al. [4]. carried out experimental studies on determining the aerodynamic and heat transfer performance of no-frost refrigerator evaporators. In both studies, water was used as media for the refrigerant side and air was used as media in the air-side of the evaporator. The experimental setups were similar: a temperature controlled water bath is used to provide desired condition of the water and evaporators were placed inside a wind tunnel. Different evaporator geometries were tested and air flow rate was also considered as a parameter in the experiments. The heat transfer coefficient and the friction factor were correlated in terms of Reynolds number and finning factor (Colburn-j factor):

$$j = 0.6976 Re_a^{-0.4842} \varepsilon^{-0.3426} \tag{1}$$

Finning factor, ε, is defined as the total tube outer area over the total outside area of the heat exchanger:

$$\varepsilon = A_o / A_{to} \tag{2}$$

Re_a is the air side Reynolds number and is defined as:

$$Re_a = \frac{d_o G_{a,max}}{\mu_a} \tag{3}$$

Here, $G_{a,max}$ represents the maximum mass flux of air and μ_a is the viscosity of air. Another correlation has been determined in order to calculate the air-side pressure drop through a no-frost fin-tube evaporator:

$$f = 5.965 Re_a^{-0.2948} \varepsilon^{-0.7671} (N/2)^{-0.4436} \tag{4}$$

A study has been conducted by Hermes et al. [5] so as to predict the energy consumption of a refrigerator using the given input conditions. A simple model has been built using steady-state simulation. This model, while avoiding the computational costs of a dynamic simulation code, provides an energy consumption prediction in agreement with the Association of the Home Appliance Manufacturers (AHAM) energy consumption tests within±5% deviation band. Runtime ratio of an on-off cycling refrigerator has to be calculated to estimate the energy consumption. The runtime ratio, τ, gives the ratio of compressor running period, τ_{on}, to the total cycle time (sum of compressor on and off periods):

$$\tau = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} \cong \frac{Q_t}{Q_e} \tag{5}$$

As the steady state simulation suggests, the thermal load, Q_t, and the cooling capacity, Q_e, are assumed to be constant during the cycling regime. If the power consumption, cooling capacity and the thermal loads are known, the overall energy consumption, in [kWh/month] can be calculated with the help of the runtime ratio. The power consumption is the sum of the power required by the compressor and the fans in the refrigerator.

In the study conducted by Kerpicci et al. [6], an experimental setup is built in order to evaluate the energy consumption of a freezer compartment. An empirical model is built to estimate the runtime for varying evaporation temperature and air flow rate values. The results showed that when these parameters are optimized, up to 13.8% energy saving could be achieved.

In another experimental study by Ghandiri and Rasti, the effects of various refrigeration system components in household refrigerator energy consumption were investigated [7]. The results showed that a reduction of 23.6% in energy consumption was possible by decreasing compressor capacity. Hot-wall condenser removal and increasing condenser air cooling increment led to refrigerant charge reduction. Replacing 0.028 in diameter capillary tube with 0.031 in alternative also led to better performance.

A parametric experimental study was conducted by Boeng and Melo in order to evaluate the effect of refrigerant charge and expansion restriction on household refrigerators [8]. After a total of 95 energy consumption measurements, it was concluded that an increase up to 30% in energy consumption was possible in case of improper selection of the investigated parameters.

Improving the efficiency of the refrigeration system is the main factor for reducing the energy consumption of household refrigerators. In order to improve efficiency, compressors having higher coefficient of performance (COP) and larger heat exchangers can be used. However, these components can increase the cost of the refrigerator and even reduce the useful volume which could be used to store food. A simpler and virtually cheaper way of improving refrigerator efficiency is to optimize system parameters. Some system parameters, such as evaporation temperature and the flow rate of the air that is blown through the evaporator, can be easily changed by minor modifications on system components (i.e. capillary tube and fan motor). In this study, these two parameters are