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Performance optimization of a two-circuit cycle with parallel evaporators for a domestic refrigerator–freezer

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ABSTRACT

A two-circuit cycle with parallel evaporators (called a "parallel cycle") for a domestic refrigerator–freezer (RF) shows energy saving potential compared with a conventional cycle with a single loop or serial evaporators because of a low compression ratio in the fresh food compartment (R)-operation. The objective of this study is to investigate the effects of the refrigerant charge, R-capillary tube, and refrigerant recovery operation on the performance of a parallel cycle. In addition, design guidelines for the heat transfer area and air flow rate of an R-evaporator are proposed. When the parallel cycle was optimized in terms of the refrigerant charge and R-capillary tube diameter, the energy consumption was reduced by 7.8% over a bypass two-circuit cycle with the same RF platform. In addition, an additional energy saving of 1.8% was obtained by the optimization of the operating sequence and refrigerant recovery operation.

Optimisation de la performance d'un cycle à deux circuits muni d'évaporateurs parallèles pour un réfrigérateur/congélateur domestique

Mots-clés : Réfrigérateur domestique ; Écoulement parallèle ; Cycle ; Performance ; Optimisation

1. Introduction

Recently, the adoption of a two-circuit cycle for domestic refrigerator–freezers (RFs) has been increasing due to its potential to enhance the energy efficiency and relative humidity of the fresh food compartment (R). Three types of two-circuit cycle have been used in general: a dual loop cycle with two compressors, a bypass two-circuit cycle, and a two-circuit cycle with parallel evaporators (parallel cycle). Generally, the dual loop cycle has strong potential to reduce the energy consumption of an RF because each loop can be individually optimized. However, this cycle requires much more cost than other two-circuit cycles due to the use of an additional compressor, condenser and suction line heat exchanger (SLHX). In addition, the dual loop cycle, which uses

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Nomenclature

A	heat transfer area (m^2)
C	clearance volume ratio
C_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
F	freezer compartment
h	enthalpy ($kJ\,kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\,h^{-1}$)
P	pressure (kPa)
PD	displacement rate ($m^3\,s^{-1}$)
P/D	pump-down
$\dot{Q}$	heat transfer rate (W)
R	fresh food compartment
RF	refrigerator–freezer
T	temperature (°C)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
υ	specific volume ($m^3\,kg^{-1}$)

Subscripts

air	air
bypass	bypass two-circuit cycle
cond	condenser
evap	evaporator
in	inlet
LMTD	log mean temperature difference
out	outlet
parallel	parallel cycle
R	fresh food compartment
ref	refrigerant
suc	suction

smaller compressors with reduced loads on each compressor (Mahesh et al., 1998; Won et al., 1994), may yield lower efficiency because a small compressor is less efficient than a big one. For the bypass two-circuit cycle, the evaporating temperature of the R-evaporator is almost the same as that of the freezer compartment (F)-evaporator. This means that the temperature difference between the refrigerant and air in the R-evaporator is relatively large, resulting in large irreversible losses and compression ratios in the R-operation. The parallel cycle will overcome these shortcomings of the above-mentioned cycles (Lu and Ding, 2006). Therefore, the parallel cycle has been applied by several home appliance companies in their household RFs.

The energy saving potential of the parallel cycle becomes large mainly at low compression ratios resulting from higher evaporating temperatures and lower evaporator pressure drops in the R-operation. The evaporator pressure drop can be reduced because the refrigerant does not pass through the F-evaporator during the R-operation. Through experimentation, Mahesh et al. (1998) reported that a parallel cycle showed 8.5% higher efficiency than a serially connected two-evaporator cycle (serial cycle); through simulation, they inferred an energy saving potential of 12.3% for identical operating conditions. Lu and Ding (2006) proposed a time-sharing running combination control strategy of a parallel cycle for improved temperature control performance under high heat load conditions. However, there are hardly any studies on the optimization of cycle components and refrigerant recovery control strategies for the parallel cycle in the open literature.

The objective of this study is to investigate the effects of the refrigerant charge, R-capillary tube, and refrigerant recovery operation on the performance of the parallel cycle. In addition, design guidelines for the heat transfer area and air flow rate of an R-evaporator are to be proposed. In the parallel cycle, the resistance of the R-capillary tube should be decreased to maximize the energy efficiency by decreasing the compression ratio in the R-operation. However, this causes an increase in the refrigerant mass flow rate and a decreased temperature difference between the refrigerant and air in the R-evaporator. In this study, to overcome these problems in the parallel cycle, the heat transfer area and air flow rate of an R-evaporator were redesigned by cycle analysis based on the equivalent specifications of a bypass two-circuit cycle. Cycle optimization in the parallel cycle was performed according to the refrigerant charge and R-capillary tube diameter. Since the refrigerant in the F-evaporator should be recovered to allow enough refrigerant flow in the R-operation of the parallel cycle, several control strategies for the refrigerant recovery operation were investigated experimentally.

2. Experimental setup and test procedure

2.1. Test apparatus

Fig. 1(a) and (b) shows schematic diagrams of a bypass two-circuit cycle and a parallel cycle, respectively. Each cycle uses a 3-way valve to control the refrigerant flow path and has two capillary tubes for each operation mode. In the bypass two-circuit cycle, the R- and F-operations are conducted consecutively with the serial flow path through the R-capillary tube and R- and F-evaporators. When the system operates at the freezer-only mode (F-operation only), the refrigerant passes though the F-capillary tube and then enters into the F-evaporator. In the parallel cycle, the R- and F-operations are carried out independently with separated, parallel flow paths. The refrigerant flows through only one of the two evaporators at a time, depending on the position of the 3-way valve. Each loop of the parallel cycle operates almost like a conventional, single-loop cycle. In many cases, a check valve is used at the F-evaporator outlet to prevent the inflow of refrigerant into the F-evaporator during the compressor's off-period. However, this may cause an additional pressure drop, which can have a negative effect on cycle performance.

Experiments were conducted in a household side-by-side (SBS) RF using R-600a. The internal volume of the RF was 0.68 m^3 (680 l). A bypass two-circuit cycle was originally adopted for the SBS RF. After performance evaluation of the original bypass two-circuit cycle, the performance of the parallel cycle was measured and then compared with that of the bypass two-circuit cycle. Table 1 lists the specifications of the original bypass two-circuit cycle. The control logic and SLHX assembly of the RF were changed to modify the bypass two-circuit cycle into the parallel cycle. As shown in Fig. 2, the SLHX assembly contained a suction pipe, F/R-capillary tube, and connecting components between the F- and R-