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W. Jun
Xi'an Jiaotong University

W. Yezheng
Xi'an Jiaotong University

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ON THE ON-OFF OPERATION IN A RECIPROCATING COMPRESSOR REFRIGERATION SYSTEM WITH CAPILLARY

Wang Jun
Wu Yezheng
Department of Power Machinery Engineering
Xi'an Jiaotong University
Xi'an, Shaanxi, China

Abstract

In some small refrigerating and air-conditioning equipment with capillary tube, the compressor is started up and shut down frequently. After shut-down the pressures in condenser and evaporator are equilibrium due to the migration of refrigerant from condenser to evaporator. When the compressor is restarted, there is a time lag to build up again the required pressures in the condenser and evaporator to the operating condition. Since the migration during off operation leads to more power input in restarting period for the small refrigerating equipment with the capillary, it is necessary to improve the refrigerating equipment by fully understanding the on-off operation characteristics. We have investigated the on-off operation in a sealed reciprocating compressor refrigerating equipment (3.48 kw). Pressure and temperature on either side of the heat exchangers during on-off operation are measured, and the power input after compressor start-up are measured too. The effect of migration during off operation on the pressure, temperature and power input has been studied. The main factors which affect the energy conversion have been analyzed. The experimental studies indicate that the prevention of refrigerant migration during off operation could reduce the power input by 4% and the peak value of power input by 9.4%. Concurrently, the cooling capacity can be increased as well as the evaporating temperature and pressure reaches the steady operating condition faster. A mathematical model of the refrigerating system in off operation is developed. The exergy losses resulted from refrigerant migration during off operation is calculated, which is the minimum value of energy to be saved by preventing the refrigerant migration during off operation.

FONCTIONNEMENT PAR TOUT OU RIEN D'UN SYSTEME FRIGORIFIQUE A COMPRESSEUR ALTERNATIF ET TUBE CAPILLAIRE.

RESUME : Dans les petites installations frigorifiques et de conditionnement d'air à tube capillaire, le compresseur démarre et s'arrête fréquemment. Après arrêt, les pressions du condenseur et de l'évaporateur sont en équilibre par suite du déplacement du frigorigène du condenseur vers l'évaporateur. Lorsque le compresseur redémarre, il y a un temps de latence avant de reconstituer les pressions nécessaires du condenseur et de l'évaporateur pour atteindre le régime de fonctionnement. La migration du frigorigène lors de l'arrêt exigeant plus d'énergie au redémarrage pour les petits appareils frigorifiques à tube capillaire, il faut améliorer le matériel frigorifique en comprenant bien les caractéristiques du fonctionnement par tout ou rien. Les auteurs ont étudié le fonctionnement par tout ou rien d'une installation frigorifique à compresseur alternatif hermétique (3,48 KW). La pression et la température de chaque côté des échangeurs de chaleur au cours du fonctionnement par tout ou rien sont mesurées ainsi que la consommation d'énergie après démarrage du compresseur. L'influence de la migration du frigorigène au cours de l'arrêt sur la pression, la température et la consommation d'énergie a été étudiée. Les principaux facteurs agissant sur la transformation de l'énergie ont été analysés. Les études expérimentales indiquent

qu'éviter la migration du frigorigène au cours de l'arrêt permettrait de réduire la consommation d'énergie de 4 % et la valeur de pointe de la consommation d'énergie de 9,4 %. En même temps, la puissance frigorifique pourrait être augmentée ainsi que la température d'évaporation et la pression atteindrait un régime stable plus rapidement. Un modèle mathématique du système frigorifique à l'arrêt est établi. Les pertes d'énergie provenant du déplacement du frigorigène au cours de l'arrêt sont calculées, ce qui est la valeur minimale de l'énergie à économiser si on évite la migration du frigorigène à l'arrêt.

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Wang, Jun   Wu, Yezheng
Reserach Assistant   Professor
Department of Power Machinery Engineering
Xi'an Jiaotong University, China (P.R.C.)

NOMENCLATURE

c	specific heat, KJ/Kg. K
E	exergy, KJ
h	specific enthalpy, KJ/Kg
m	mass flow rate of refrigerant, Kg/s
M	mass, Kg
p	pressure, KPa
Q	heat transfer rate, KW
s	specific entropy, KJ/Kg. K
t	time, s
T	temperature, K
u	specific internal energy, KJ/kg
V	velocity, m/s

Subscripts

a	air side	c	condenser
ca	capillary tube	co	compressor
e	evaporator	r	refrigerant
s	compressor shell	w	wall
1	condenser inlet	2	condenser outlet
3	evaporator inlet	4	evaporator outlet

INTRODUCTION

In some small refrigerators and air-conditioners, the compressor starts up and shuts down frequently due to the capacity control. Therefore, it is essential to study the working characteristics of the on-off cycle and the factors which affect the energy conversion during the on-off cycle. Some research works have been done on the start-up characteristics of the system,[1],[2] without the consideration of effects caused by refrigerant migration during the on-off cycle. Fumiv Matsuoka[3] investigated the on-off operation effects in an air-conditioner equiped with a built-in rotary compressor. It was reported that the energy losses during the start-up would be reduced by 20% if the refrigerant migration was prevented after the compressor shut-down.

Since reciprocating compressors are widely used in air-conditioner, it is necessary to study the on-off operating characteristics of an air-conditioner equiped with a sealed reciprocating compressor as shown in Fig.1. On the basis of experiments, the authors have studied the effects of refrigerant migration in different on-off cycles. The experimental studies indicate that preventing refrigerant from migration during off cycle would reduce the power input by 4% and increase the cooling capacity. Besides, the evaporating temperature and pressure reach the steady operating condition faster.

TEMPERATURE PRESSURE AND POWER INPUT

The experimpents have been done in two cases:

Case 1 Conventional cycle with the refrigerant migration through the capillary tube after compressor shut-down.

Case2 To cut off the magnetic valve M2 as soon as the compressor shut-down, as shown in Fig.1, so as to prevent the refrigerant in the condenser from migration. M1 and M3 are used as by-pass valves between the compressor suction and discharge manifolds. The valves open rapidly during the start stage to avoid the excessive motor torque.

The measurements lasted 7 min. in both the on cycle and the off cycle. The temperatures are 32°C outside the condenser and 18°C outside the evaporator.

Fig.2 and Fig.3 show the inlet and outlet temperature responses of the refrigerant in condenser and evaporator during the off cycle. Since the mixing of refrigerant in the condenser and the evaporator is stoped, the inlet and outlet temperature of the condenser and the evaporator vary smoothly than they do in Case1. During the off cycle, the refrigerant temperature and pressure inside the condenser fall continuously. When the refrigerant temperature inside the condenser approximately equals the environmental temperature, the refrigerant motion at condenser outlet becomes a main effect on refrigerant temperature change. The refrigerant flow rate reduces as the pressure difference between the condenser and the evaporator decreases. Heat transfer makes the temperatures inside and outside the condenser equilibrate. That is the reason why the refrigerant temperature at the condenser outlet is concave as shown in Fig.2 and the minimum temperature is lower than the temperature outside the condenser. Fig.4 and Fig.5 show the refrigerant temperature during the on cycle. In Case1, the liquid flows through capillary from condenser into evaporator after shut-down. It is estimated that the refrigerant staying in the condenser after migration account for 20% of the total charge(4). However, the situation is just the opposite in Case2, the liquid is mainly in condenser. When the compressor starts, evaporating temperature reduces faster. Since the mass flow rate in caprillary is lower than it in the suction line of the compressor, the temperature rises again at the evaporator outlet. This phenomenon lasts longer in Case2 as a magnetic valve located near the capillary.

The pressure responses during the off cycle in Case1 and Case2 are shown in Fig.6 and Fig.7. In Case1 the pressure response is affected by refrigerant migration and heat transfer during the off cycle. The final equilibrium pressure is saturated pressure corresponding to the temperature outside the evaporator. In Case2, the pressure changes during the off cycle are only affected by heat transfer so that the refrigerant pressure inside the condenser and the evaporator are the saturated pressure corresponding to their outside temperature respectively and can not reach equilibrium at all. The pressure and the temperature responses during the on cycle in Case1 and Case2 are similar. It is observed from Fig.8 and Fig.9 that the evaporating pressure after start-up decreases faster in Case2. In this case, the cooling capacity can be increased during the on cycle as liquid fully evaporate in evaporator.

Fig.10 shows the compressor electrical power input during the on cycle in both cases. After 80 seconds, the power input in both cases will be the same. If the refrigerant is prevented from migration during the off cycle, the peak value of power input will drop to about 9.4% and the total power value will reduce by 4% during the on cycle. During the start-up the heat inertia of each part of the equipment influences the pressure and temperature and causes energy losses. The system will reach steady operation more quickly by reducing the heat inertia and result in energy saving. Increasing the heat inertia of equipments makes the pressure and temperature variation flatter and causes more refrigerant flow from condenser to evaporator during the off cycle in Case1. Therefore, the start operation prolongs and the energy input increases.

CALCULATION OF ENERGY LOSSES CAUSED BY REFRIGERANT MIGRATION

The energy loss caused by refrigerant migration during shut-down cycle and heat inertia of the equipments is:

$$\Delta E = E_1 - E_2 = \int_0^t \left[E_1(t) - E_2(t) \right] dt \qquad (1)$$

where E_1 is the exergy losses in Case1 during the off cycle. E_2 is the exergy losses in Case2 during off cycle. $E_1(t)$ and $E_2(t)$ are the exergy losses in both cases respectively at t moment during the off cycle. The system exergy losses consist of the losses in condenser, evaporator, compressor and capillary tube. The loss ΔE is the minimum value of energy saving by preventing refrigerant from migration. The refrigerant flow and heat transfer during the off cycle are nonsteady processes, so a simple transient model to calculate the exergy loss during the off cycle has been developed.

The exergy equation in condenser is given as follows:

$$\frac{dE_c}{dt} = T_a \frac{d(M_r s_r)}{dt} + T_a s_2 m_2 - (h_2 + \frac{V_2}{2})\, m_2 - \frac{d(M_r u_r)}{dt} - M_{cw} C_{cw} \frac{dT_{cw}}{dt} \qquad (2)$$

The exergy loss of refrigerant flowing through capillary tube is:

$$\frac{dE_{ca}}{dt} = T_a\ m_2 (s_3 - s_2) \qquad (3)$$

During the shut-down in Case2, there is no refrigerant flowing through capillary tube.

The exergy losses in evaporator is:

$$\frac{dE_e}{dt} = T_a \frac{d(M_r s_r)}{dt} + T_a (s_4 m_4 - s_3 m_3) + (h_3 + \frac{V_3}{2}) m_3 - (h_4 + \frac{V_4}{2}) m_4 - \frac{d(M_r u_r)}{dt} -$$

$$M_{ew} C_{ew} \frac{dT_{ew}}{dt} + Q_e (1 - \frac{T_a}{T_{ae}}) \qquad (4)$$

The exergy loss in compressor is given as follows:

$$\frac{dE_{co}}{dt} = T_a \frac{d(M_r s_r)}{dt} - T_a s_4 m_4 + (h_4 + \frac{V_4}{2}) m_4 - \frac{d(M_r u_r)}{dt} -$$

$$M_{sw} C_{sw} \frac{dT_{sw}}{dt} - M_{cow} C_{cow} \frac{dT_{cow}}{dt} + T_a \Big(Q_{co} \big(\frac{1}{T_r} - \frac{1}{T_{cow}} \big) +$$

$$Q_{rs} \big(\frac{1}{T_{sw}} - \frac{1}{T_r} \big) \Big) \qquad (5)$$

The exergy losses in both Case1 and Case2 can be calculated by the above equations during shut-down. The difference of the exergy losses in both cases is the minimum value of energy saving in Case2.

CONCLUSIONS

1. In refrigeration system, the shut-down transient has a great influence on start-up transient. By preventing refrigerant from migration during shut-down, the energy losses in start-up could be reduced and the start-up transient charicteristics would be improved.
2. By preventing refrigerant from migration during shut-down, the motor power input during start-up decreases by 4%, the peak value drop to about 9.4%, and the evaporating temperature lower rapidly. All of these are beneficial to cooling capacity of start-up.
3. The heat inertia of refrigeration equipments should be as small as possible for dynamic behavior.
4. A computer program for simulating the shut-down transient behavior of a hermetic compressor refrigeration system has been developed. It can be used to calculate the exergy loss due to the refrigerant migration. The result is the minimum value of energy saving during on-off cycle by preventing refrigerant from migration after shut-down.

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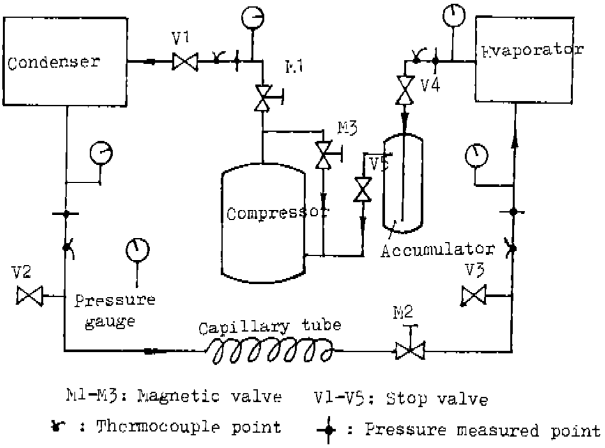

Fig. 1 Test equipment

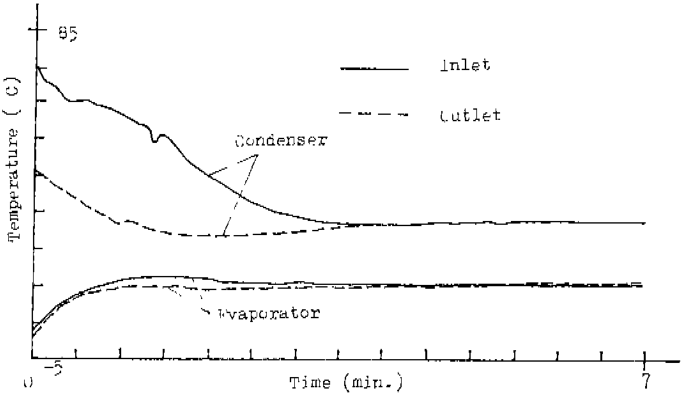

Fig. 2 Shut-down in Case1

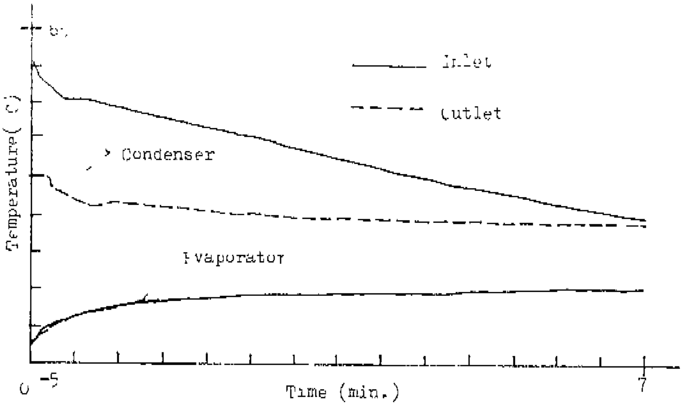

Fig. 3 Shut-down in Case2

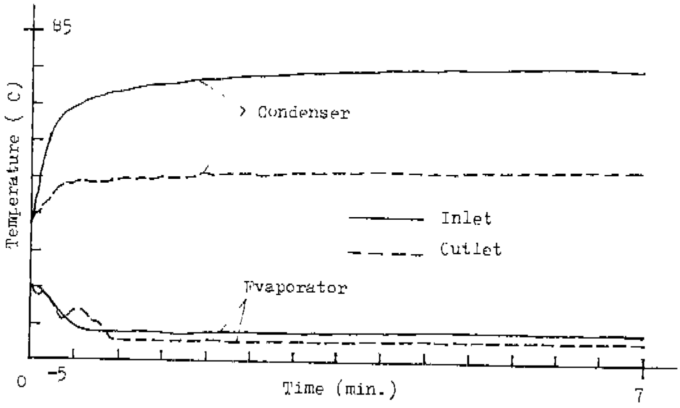

Fig. 4 Start-up in Case1

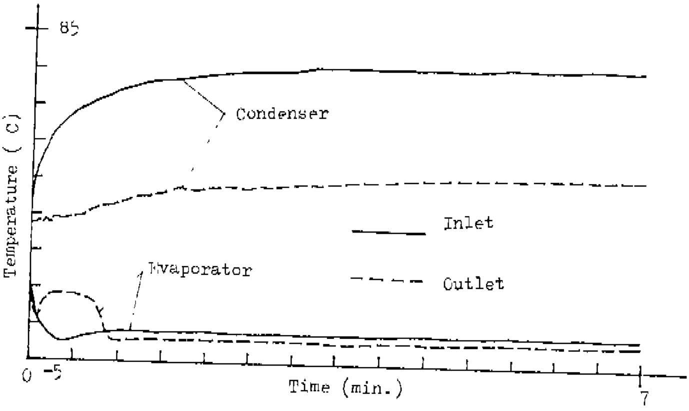

Fig. 5 Start-up in Case2

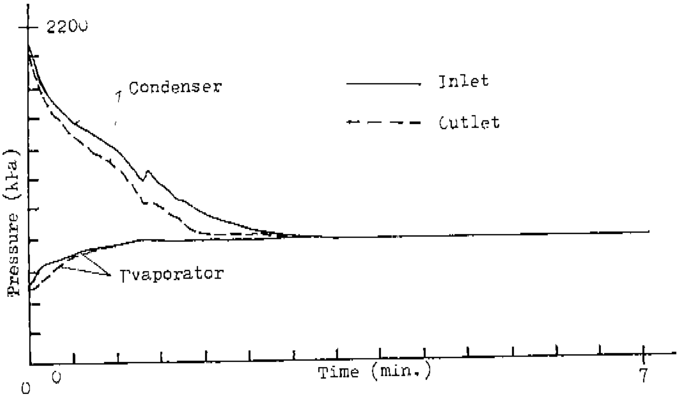

Fig.6 Shut-down in Case1

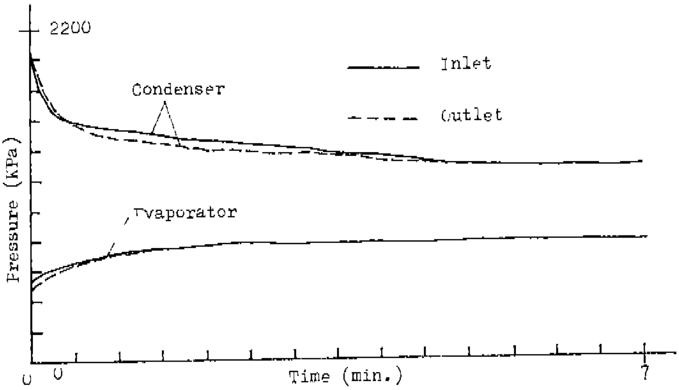

Fig. 7 Shut-down in Case2

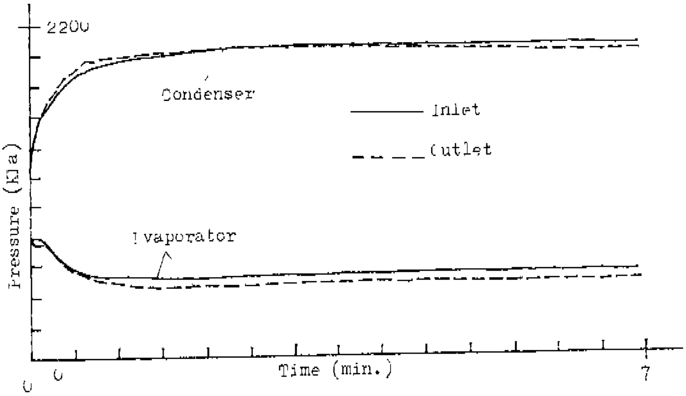

Fig. 8 Start-up in Case1

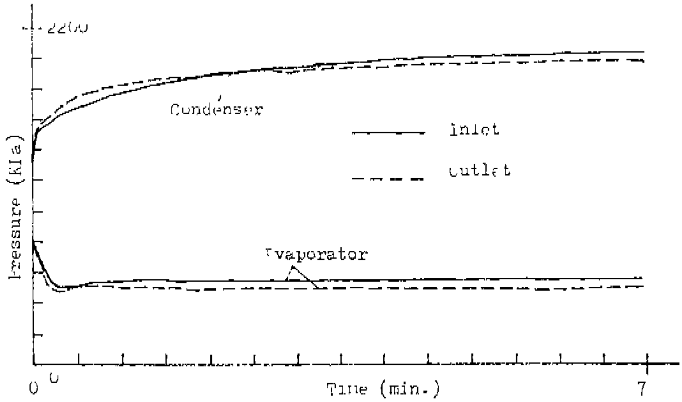

Fig. 9 Start-up in Case2

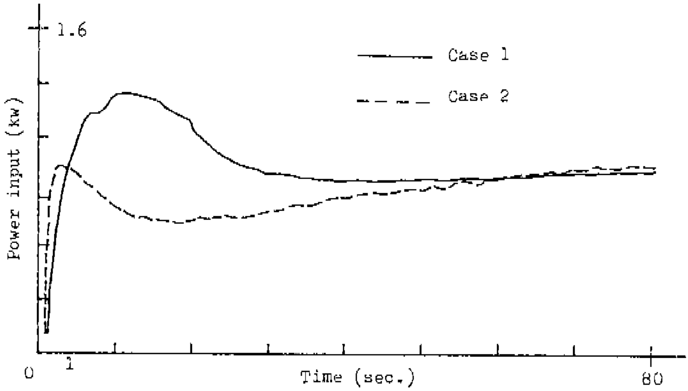

Fig. 10 Start-up power input