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The Optimal Ratio of the Temperature Differences for Heat Transfer in Evaporator and Condenser

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Abstract: In the design of a refrigeration / heat pump system, the selections of the temperature differences for heat transfer (i.e., in the evaporator it is the temperature difference between the low temperature heat source and the refrigerant, and in the condenser, between the refrigerant and the high temperature heat source) are based on some kind of "rule of thumb". To be more scientifically in the design, this paper presents the optimal ratio of the temperature differences for heat transfer in the evaporator and in the condenser, from the second law (the entropy or the exergy) analysis. That is the optimal ratio is the ratio of the temperature of the low-temperature heat source (heat source) to the temperature of the high-temperature heat source (heat sink). This finding is called "You's Principle".
Keywords: Optimal ratio of the temperature differences for heat transfer, Evaporator, Condenser, entropy analysis, You's Principle

I. INTRODUCTION

In the design of a refrigeration / heat pump system, the selections of the temperature differences for heat transfer (i.e., in the evaporator it is the temperature difference between the low temperature heat source and the refrigerant, and in the condenser, between the refrigerant and the high temperature heat source) are based on some kind of "rule of thumb". For example, for an air conditioner, the temperature difference in the evaporator is about 15K, and in the condenser is about 10K (Arora [1]). To be more scientifically in the design, this paper investigated the optimal ratio of the temperature differences for heat transfer in the evaporator and the condenser, from the second law (the entropy or the exergy) analysis. The study shows that the optimal ratio of the temperature differences for heat transfer in the evaporator and in the condenser is the ratio of the temperatures of the low-temperature heat source (heat source) to that of the high-temperature heat source(heat sink). This finding is called "You's Principle".

II. THE ENTROPY ANALYSIS ON REFRIGERATION / HEAT PUMP CYCLE

A. *The General Equation for Entropy Generation*

The entropy analysis is the evaluating of the entropy generation in each component.
Recall from Thermodynamics (Cengel et al [2], Ganesan [3]), for a steady flow with one inlet and one exit, we have

$$\dot{S}_g = \dot{m}(s_e - s_i) - \int_1^2 \frac{\delta Q}{T} \qquad 1$$

where $\dot{S}_g$ is the entropy generate rate of the component analysed, $\dot{m}$ is the mass flow rate of the working fluid, and for refrigeration or heat pump cycle, the fluid is refrigerant, s_i and s_e are the entropy of the fluid entering and leaving the component, respectively, Q is the heat transferred to or from the heat source (between the heat source and the refrigerant), and T is the temperature of the heat source.
Therefore, for the refrigeration or heat pump cycle, we can write the entropy generation rate for a component as:

$$\dot{S}_g = \dot{m}_{ref}(s_e - s_i) - \int_1^2 \frac{\delta Q}{T_{sour}} \qquad 2$$

where $\dot{m}_{ref}$ is the mass flow rate of the refrigerant.
For the refrigeration or heat pump, normally, the temperatures of the heat sources are changed, saying, from $T_{sour,1}$ to $T_{sour,2}$. Therefore, Eq. 2 can also be written as:

$$\dot{S}_g = \dot{m}_{ref}(s_e - s_i) - \dot{m}_{sour} c \ln \frac{T_{sour,2}}{T_{sour,1}} \qquad 3$$

where $\dot{m}_{sour}$ is the mass flow rate of the stream of the heat source, and c is the specific heat of the heat source. If the heat source is a gas, the specific heat will be the specific heat of the gas at constant pressure.
Eq. 3 is the general equation for the entropy analisis on Refrigeration / Heat Pump cycle.

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B. The Entropy Analysis on Refrigeration / Heat Pump Cycle

Refer to Fig.1, the diagram of a refrigeration / heat pump cycle in the T-s diagram.

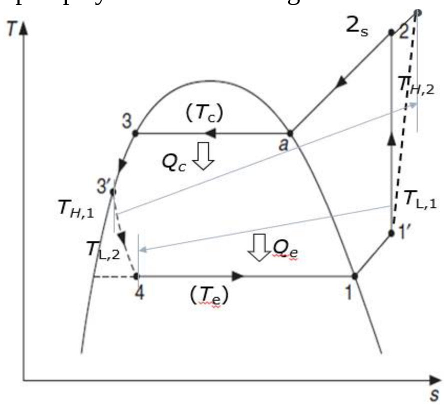

Figure 1: The Vapor Compression Refrigeration / Heat Pump Cycle in the T-s diagram

1) The Compressor

For the compressor, neglect the heat exchange between the compressor and the environment. From Eq.3, we have

$$\dot{S}_{g,comp} = \dot{m}_{ref}(s_2 - s_{1'}) \quad 4$$

2) The Expansion Valve

For the expansion valve, again, we can neglect the heat exchange between the compressor and the environment. From Eq.3, we have

$$\dot{S}_{g,valve} = \dot{m}_{ref}(s_4 - s_{3'}) \quad 5$$

3) For the Evaporator

In the evaporator, the refrigerant absorbs heat, so Q_e >0, however, for the heat source, dT_L<0. From Eq.3, we have

$$\dot{S}_{g,evap} = \dot{m}_{ref}(s_{1'} - s_4) - (-\dot{m}_L c_L \ ln\frac{T_{L,2}}{T_{L,1}}) \quad 6$$

where $\dot{m}_L$ and c_L are the mass flow rate and the specific heat of the stream of the low-temperature heat source, respectively.
If we use the concept of the isolated system, we can also write that

$$\dot{S}_{g,evap} = \Delta S_{system} + \Delta S_{enviroment} = \Delta S_{ref} + \Delta S_{sour,L}$$

where the system is the refrigerant, and the environment is the low-temperature heat source.
For simplification, assuming the temp of the refrigerant is kept at T_e, or $T_{e,avg}$ (here we use T_e, not T_0 to represent the evaporator temperature, since in the exergy analysis, T_0 is used to represent the environment temperature).

$$\dot{m}_{ref}(s_{1'} - s_4) = \dot{m}_{ref}(h_{1'} - h_4)/T_{e,avg} \quad 7$$

Remember that the heat released by the Low-temp heat source equals to the heat absorbed by the refrigerant

$$Q_e = \dot{m}_{ref}(h_{1'} - h_4) = \dot{m}_L c_L (T_{L,1} - T_{L,2}) \quad 8$$

Here we use Q_e (or Q_L) to represent the evaporator's capacity (or cooling capacity).

Therefore,

$$\dot{S}_{g,evap} = Q_e(\frac{1}{T_{e,avg}} - \frac{ln(T_{L,1}/T_{L,2})}{T_{L,1} - T_{L,2}}) = Q_e(\frac{1}{T_{e,avg}} - \frac{1}{T_{L,avg}}) \quad 9$$

From Eq.9, it can be seen that to reduce the entropy generation, we need to make the temperatures of the evaporator and the low temperature heat source (heat source here) as close as possible

4) For the Condenser

In the condenser, the refrigerant releases heat, so Q_c <0, however, for the heat source, dT_H>0. From Eq.3, we have

$$\dot{S}_{g,cond} = \dot{m}_{ref}(s_{3'} - s_2) - (-\dot{m}_H c_H \ ln\frac{T_{H,2}}{T_{H,1}}) \quad 10$$

where $\dot{m}_H$ and c_H are the mass flow rate and the specific heat of the stream of the high-temperature heat source, respectively.

If we use the concept of the isolated system for the condenser, we can also write that

$$\dot{S}_{g,evap} = \Delta S_{system} + \Delta S_{enviroment} = \Delta S_{ref} + \Delta S_{sour,H}$$

where the system is the refrigerant, and the environment is the high-temperature heat source.

As for the evaporator, for the condenser, it can be derived that

$$\dot{S}_{g,cond} = Q_c\left(\frac{1}{T_{H,ave}} - \frac{1}{T_{c,avg}}\right) \quad 11$$

and the average condenser temperature can be found by

$$\dot{m}_{ref}(s_3, -s_2) = \dot{m}_{ref}(h_3, -h_2)/T_{c,avg} \quad 12$$

Here we use Q_c (or Q_H) to represent the condenser's capacity (or heating capacity), and T_c (not T_k) to represent the condenser temperature, since symbols such as T_j and T_k are quite often used to represent the temperature of the heat sources (Cengel et al [2]).
From Eq.10, it can be seen that to reduce the entropy generation, we need to make the temperatures of the condenser and the high temperature heat source (heat sink here) as close as possible.

5) For the whole system

$$\dot{S}_{g,sys} = \dot{S}_{g,comp} + \dot{S}_{g,valve} + \dot{S}_{g,cond} + \dot{S}_{g,evap}$$

To improve the efficiency of the system, it is necessary to find out which component(s) has the relatively high entropy generation.
Since we cannot do much on the compressor and the expansion valve, the condenser and the evaporator will be the two components to be studied.
Therefore, we need to improve either the condenser or the evaporator, or both, whichever the entropy generation is higher.

C. You's Principle – The optimal ratio of the temperature differences for heat transfer in condenser and evaporator

1) From Entropy Analysis

Since we need to improve either the condenser or the evaporator, whichever the entropy generation is higher. Ideally, the entropy generations in the two components should be the same, i.e.,

$$Q_c\left(\frac{1}{T_{H,avg}} - \frac{1}{T_{c,avg}}\right) = Q_e\left(\frac{1}{T_{e,avg}} - \frac{1}{T_{L,avg}}\right) \quad 13$$

To simplify the derivation, let's investigate a Carnot refrigeration / heat pump cycle, as shown in Fig.2.

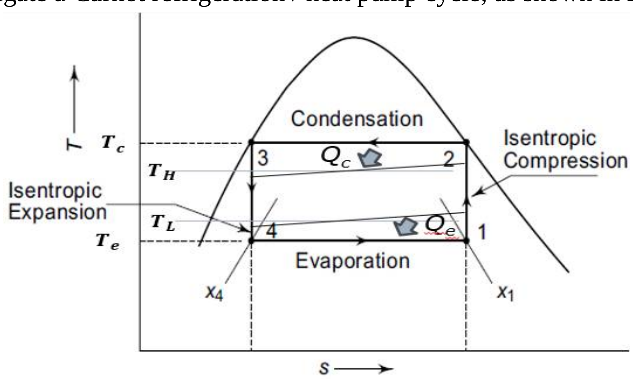

Figure 2: The Carnot Refrigeration / Heat-pump Cycle in the T-s diagram

For a Carnot cycle, from Fig 2,we can see that

$$Q_c = T_c(S_2 - S_3), \quad Q_e = T_e(S_1 - S_4), \quad \text{and } (S_2 - S_3) = (S_1 - S_4)$$

So we can derive that:

$$\frac{Q_e}{Q_c} = \frac{T_e}{T_c} \quad 14$$

and

$$\frac{T_{L,avg} - T_e}{T_c - T_{H,avg}} = \frac{T_{L,avg}}{T_{H,avg}} \quad 15(a)$$

In reality, besides the temperatures of the heat sources in the heat exchangers, the temperatures of the refrigerant in the heat exchangers, particularly in the condenser, are changes as well. In that case, the average temperature can be used here, and the conclusion is still valid, i.e.,

$$\frac{T_{L,avg} - T_{e,avg}}{T_{c,avg} - T_{H,avg}} = \frac{T_{L,avg}}{T_{H,avg}} \quad 15(b)$$

The average evaporator temperature and the average condenser temperature can be evaluated from Eq.7 and Eq. 12.

That is You's Principle, which states that *in the heat exchangers' design, the optimal ratio of the temp differences for heat transfer in the evaporator and in the condenser is the ratio of the temperature of the Low-temp heat source to the temperature of the high-temp heat source*. Remember, these temperatures are the absolute temperatures (e.g., in K).

2) From Exergy Analysis

This relationship can also be derived by exergy analysis.

Refer to Fig.2, in the evaporator, the exergy change of the refrigerant is (Moran [4]):

$$Ex_e = (\frac{T_0}{T_e} - 1)Q_e \qquad 16$$

and the exergy change of the low temperature heat source is:

$$Ex_L = (\frac{T_0}{T_{L,avg}} - 1)Q_e \qquad 17$$

and $Ex_e > Ex_L$, so the exergy destroyed in the evaporator is

$$Ex_e - Ex_L = (\frac{T_0}{T_e} - \frac{T_0}{T_{L,avg}})Q_e \qquad 18$$

In the condenser, the exergy of the refrigerant is:

$$Ex_c = (1 - \frac{T_0}{T_c})Q_c \qquad 19$$

and the exergy change of the high temperature heat source is:

$$Ex_H = (1 - \frac{T_0}{T_{H,avg}})Q_c \qquad 20$$

and$Ex_c > Ex_H$, so the exergy destroyed in the condenser is

$$Ex_c - Ex_H = (\frac{T_0}{T_{H,ave}} - \frac{T_0}{T_c})Q_c \qquad 21$$

To make the exergy destructions in the evaporator and the condenser the same, we have

$$(\frac{T_0}{T_e} - \frac{T_0}{T_{L,avg}})Q_e = (\frac{T_0}{T_{H,ave}} - \frac{T_0}{T_c})Q_c \qquad 22$$

and

$$\frac{T_{L,avg} - T_e}{T_c - T_{H,avg}} = \frac{T_{L,avg}}{T_{H,avg}} \qquad 15(a)$$

III. CONCLUSIONS

From Second law analysis (entropy analysis), this paper reveals that in the heat exchangers' design for a refrigeration /heat-pump system, the optimal ratio of the temp differences for heat transfer in the evaporator and in the condenser is the ratio of the temperature of the low-temp heat source to the temperature of the high-temp heat source. This conclusion is called You's Principle.

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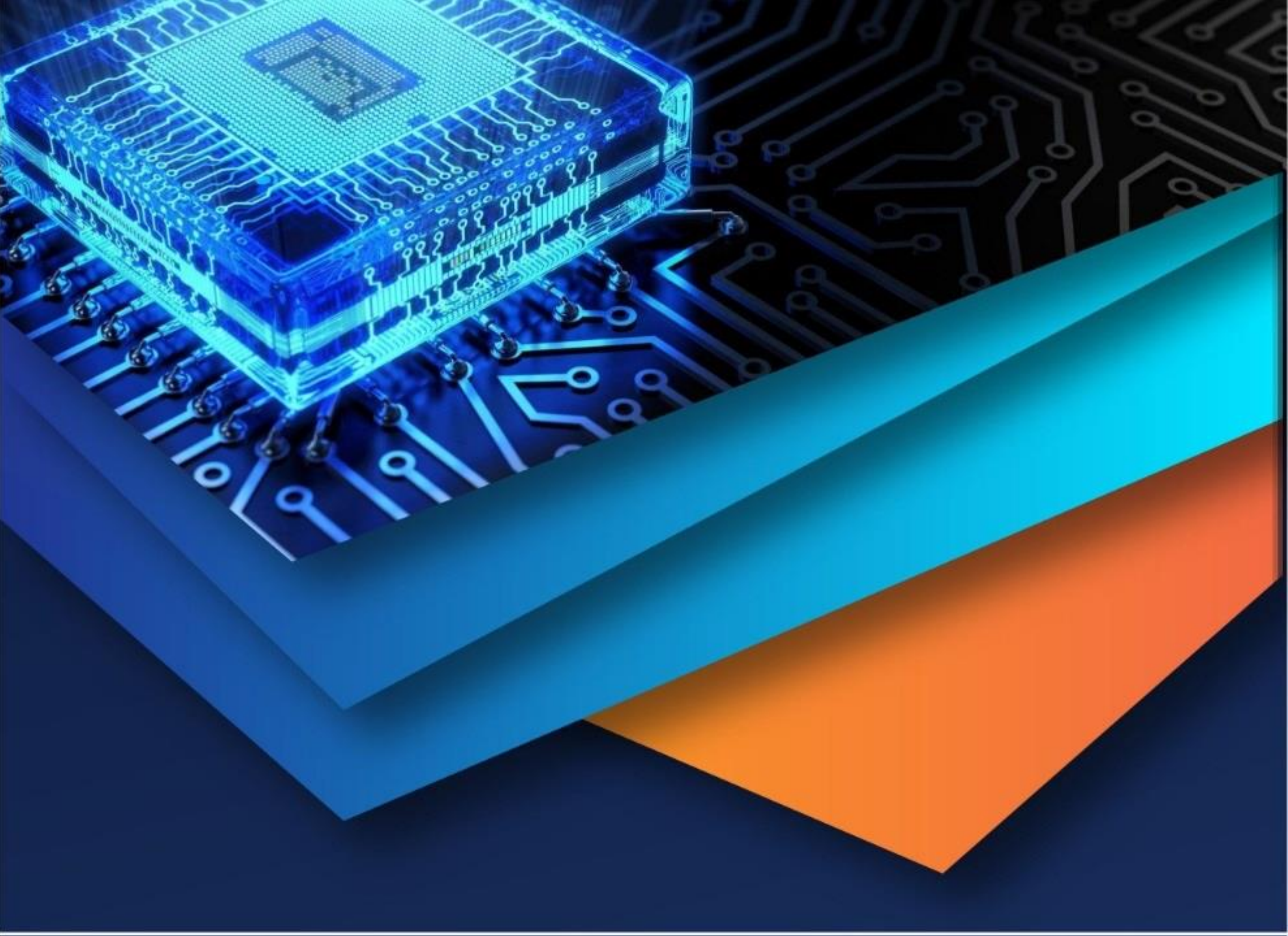

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