High Temperature Air to Water Heat Pumps In a two circuit cascade System.

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It's not like we discovered the fire!

Over the last few years there's a need of replacing oil boilers with heat pumps. These heat pumps will be used in central heating systems keeping the existing radiators.

So that the static radiators may be efficient, in today existing facilities, hot water temperatures of 80^0C are required. Hense, air to water heat pumps manufacturers are moving towards creating the right devices. Therefore, cascade connections have made a come-back. In the past, cascade connections were used for degrading the cooling temperatures and in this article follows a detailed analysis of cascade refrigerant systems.

We would like to note that:

1. In cascade cases, different refrigerant fluids are used for each circuit.
2. The condensation heat of each circuit is absorbed by the evaporator of the next circuit.
3. It is about more than one cooling circuits and not for a two or more stage- compression.

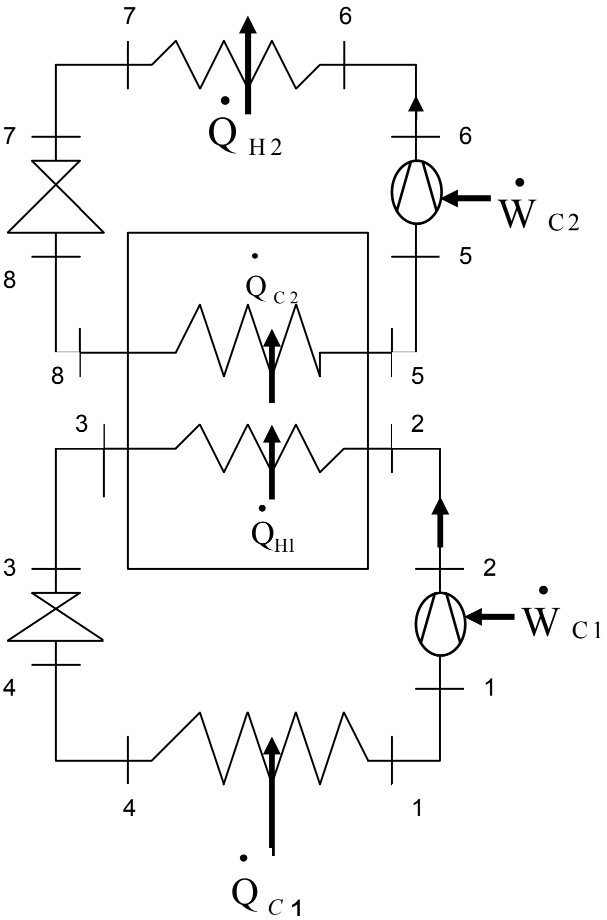

Figure (1)

Symbolism:

$\dot{Q}_{H2}$: The condensation heat load of the second compression circuit (this is released to the environment).

$\dot{Q}_{H1}$: The heat load of the first condensation compression circuit.

$\dot{Q}_{C}$: The absorbed cooling load.

$\dot{W}_{C1}$: The compressor's Power of the first circuit.

$\dot{W}_{C2}$: The compressor 's Power of the second circuit.

$COP_{\theta1}$: The Coefficient Of Performance of the first circuit in heating mode.

$COP_{\theta2}$: The Coefficient Of Performance of the second circuit in heating mode.

$COP_{\psi o\lambda}$:The Total Coefficient Of Performance in cooling mode.

$COP_{\psi1}$: The Coefficient Of Performance in cooling of the first coolant circuit.

$COP_{\psi2}$: The Coefficient Of Performance in cooling of the second coolant circuit.

$COP_{\theta o\lambda}$: The total Coefficient Of Performance of the heating system.

Figure (1) depicts the arrangement of a refrigerating machinery installation of two refrigerant circuits.

From the energy balance of figure (1) we get:

$$\dot{W}_{C1}+\dot{W}_{C2}+\dot{Q}_{C}=\dot{Q}_{H2} \quad \text{...(1)}$$

$$\text{If} \quad \frac{\dot{W}_{C2}}{\dot{W}_{C1}}=\alpha \quad \text{.. (2)}$$

$$\mathrm{C.O.P}_{\theta o\lambda}=\frac{\dot{Q}_{H2}}{\dot{W}_{C1}+\dot{W}_{C2}}=\frac{\dot{Q}_{H2}}{\dot{W}_{C1}\,(\alpha+1)}=\frac{\dot{W}_{C1}+\dot{W}_{C2}+\dot{Q}_{C}}{\dot{W}_{C1}\,(\alpha+1)}=$$

$$=\frac{1}{1+\alpha}+\frac{\alpha}{1+\alpha}+\frac{\mathrm{C.O.P.}_{\Psi 1}}{1+\alpha}=1+\frac{\mathrm{C.O.P.}_{\Psi 1}}{1+\alpha} \quad \text{..............................(3)}$$

$$\mathrm{C.O.P}_{\Psi o\lambda}=\frac{\dot{Q}_{C}}{\dot{W}_{C1}+\dot{W}_{C2}}=\frac{\dot{Q}_{C}}{\dot{W}_{C1}+\alpha\cdot\dot{W}_{C1}}=\frac{\dot{Q}_{C}}{\dot{W}_{C1}\,(1+\alpha)}=\frac{\mathrm{C.O.P.}_{\Psi 1}}{1+\alpha} \quad \text{.................... (4)}$$

The absorbed $\dot{Q}_{C}$ remains constant and independent, whether we have one circuit (conventional heat pump) or two compression circuits (high temperature heat pump in a cascade system).

In the case of one circuit system as shown in Figure 2 we get:

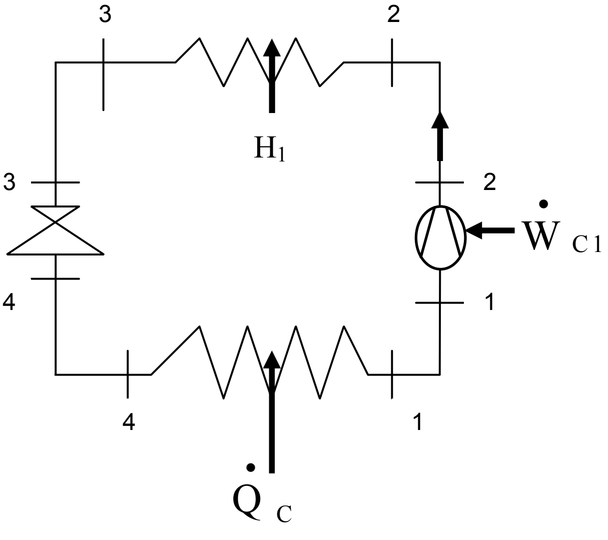

Figure (2)

$$\dot{W}_{C1}+\dot{Q}_{C}=\dot{Q}_{H1} \quad \text{.. (5)}$$

$$\mathrm{C.O.P}_{\Theta 1}=\frac{\dot{Q}_{H1}}{\dot{W}_{C1}} \quad \text{... (6)}$$

$$C.O.P_{\Psi 1} = \frac{\dot{Q}_{C}}{\dot{W}_{C1}} \quad \ldots\ldots (7)$$

Comparing the equations (3), (6) we find:

$$\frac{\dot{Q}_{C}}{\dot{W}_{C1}} \rangle \frac{\dot{Q}_{C}}{\dot{W}_{C1}+\dot{W}_{C2}} \quad \text{or} \quad C.O.P_{\Psi,1} \rangle C.O.P_{\Psi,o\lambda} \quad \ldots\ldots (8)$$

which is a much higher efficiency of the heat pump in a simple circuit system, when it operates in cooling mode.

In case that $W_{C1}=W_{C2}$ then from Eq.(7) and Eq.(3) we get:

$$C.O.P._{\psi o\lambda} = \frac{\dot{Q}_{\Psi}}{\dot{W}_{C}+\dot{W}_{C2}} = \frac{\dot{Q}_{\Psi}}{2\dot{W}_{C2}} = \frac{1}{2}\cdot C.O.P_{\Psi 1} \quad \ldots\ldots (9)$$

The expepted C.O.P of a cascade refrigeration system , is half the C.O.P in a single circuit refrigeration cooling system.

With the use of Eq.(1) we understand that in the two cirquit installation the $\dot{Q}_{H2}$ is greater than Q_{H1} by W_{C2} which is paid to the electricity bill with the ratio one to one (1/1). The compressor C_2 does not draw any amounts of heat from the environment and therefore the efficiency of the installation doesn't increase. The temperature rise happens due to the second compressor.

The apocalypse:

For the Performance in heating we get:

$$C.O.P_{\Theta 1} = \frac{\dot{Q}_{H1}}{\dot{W}_{1}} \quad \ldots\ldots (10)$$

$$C.O.P_{\Theta,o\lambda} = \frac{\dot{Q}_{H2}}{\dot{W}_{C1}+\dot{W}_{C2}} = \frac{\dot{Q}_{H2}}{\frac{\dot{W}_{C2}}{\alpha}+\alpha\times\dot{W}_{C2}} = \frac{\dot{Q}_{H2}}{\dot{W}c_2\,(\frac{1}{\alpha}+1)} = \frac{\dot{Q}_{H2}}{\dot{W}c2}\times\frac{1}{(1+\frac{1}{\alpha})} \quad \ldots\ldots (11)$$

or

$$C.O.P_{\Theta,o\lambda} = [C.O.P_{\theta 2}]\cdot\frac{1}{\frac{\alpha}{\alpha}\;1+\frac{1}{\alpha}} = \frac{\alpha}{1+\alpha}\cdot[C.O.P_{\theta 2}] \quad \ldots\ldots (12)$$

$$C.O.P_{\Theta o\lambda} = \frac{\dot{Q}_{H2}}{\dot{W}_{C1}+\dot{W}_{C2}} = \frac{\dot{Q}_{H1}+\dot{W}_{C2}}{\dot{W}_{C1}+\dot{W}_{C2}} = \frac{\dot{Q}_{H1}+W_{C2}}{\dot{W}_{C1}+\alpha\dot{W}_{C1}} = \frac{\dot{Q}_{H1}+\dot{W}_{C2}}{\dot{W}_{C1}(1+\alpha)} \quad \ldots\ldots (13)$$

or

$$C.O.P_{\theta o\lambda} = \frac{\dot{Q}_{H1}}{\dot{W}_{C1}\cdot(1+\alpha)} + \frac{\dot{W}_{C2}}{\dot{W}_{C1}\cdot(1+\alpha)} = [C.O.P_{\theta 1}]\cdot\frac{1}{(1+\alpha)} + \frac{\dot{W}_{C2}}{\dot{W}_{C1}}\cdot\frac{1}{(1+\alpha)} \quad \ldots\ldots (14)$$

or

$$C.O.P_{\Theta o\lambda} = \left[C.O.P._{\Theta 1}\right] \cdot \frac{1}{(1+\alpha)} + \frac{\alpha}{(1+\alpha)} \Rightarrow \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

or

$$C.O.P_{\Theta,o\lambda} = \frac{C.O.P_{\Theta 1}+\alpha}{1+\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

In this analysis there's no use of Fans or water Pumps and therefore there's no energy consumption in the condensers and evaporators.

Conclusions

High temperatures Heat pumps are designed to replace oil boilers mainly in houses, 2 and 3 storey buildings or wherever else legal concerns are not implicated. From the previous analysis we've made the following conclusions:

1. The efficiency rate of the refrigeration cycle in high temperatures cascade connections depends on the ratio **a** of the two compressor's Power eg. for a=1 we get $C.O.P_{\theta o\lambda}$ 2.15 when the $C.O.P_{\theta 1}=3.3$. The $C.O.P_{\theta o\lambda} = 2.15$ corresponds to 1 cascade cycle heat pump and the $C.O.P_{\theta 1}=3.3$ corresponds to a conventional heat pump of 1 cooling cycle.
2. For a=1,5 and the $C.O.P_{\theta 1}=3.3$ it is respectively $C.O.P_{\theta o\lambda}=1.92$.
3. We did not take into consideration the C.O.P change in relation to the environment's temperature. In this case, the reduction of C.O.P makes the heat pumps of this particular type more unprofitable eg. at 0°C the performance is reduced about 20% compared to the performance achieved at 7°C.
4. It is impossible today to find a high temperature cascade heat pump which belongs to the A energy class, as shown in the Eq.(15).
5. The high complexity of the Cascade system will cause many problems when it comes down to technically supporting the system.
6. Because of the existence of internal and external units which are connected with pipes, within which circulate refrigerant fluids (not water), here are certain requirements which have to be met such as the right pipe lengths and specific mounting positions.
7. Filling with coolant the additional pipe lines.
8. These two circuit units do not operate in cooling mode.
9. Techno-economic solutions should be considered for the applications mentioned below:

   a. the use of conventional heat pump and the replacement of radiators with fan coils in the same pipeline system, for heating and cooling functions.

   b. the use of high temperature cascade heat pump using the existing radiators and pipeline system without perspective cooling.

   c.
   - Use of a Conventional heat pump.
   - Use of the existing radiators and pipelines.
   - Coverage up to a certain environmental temperature.
   - Assistance with the second source for low temperatures eg. < 7 °C.

10. If the ratio **a** of the compressor's Power of the two circuits is less than **1** the C.O.P_θ is reduced significantly.

11. Due to its way of functioning, a two refrigerant cycle heat pump can not operate in cooling mode. This is a major disadvantage of such heat pumps compared to the conventional heat pumps of one refrigerant circuit which operate in heating and cooling mode.

OUR PROFITS IN AN EXAMPLE

Supposing that the required heat load of a house is $\dot{Q}_{H2}$= 16 KW.

C.O.P in heating, using conventional one circuit heat pump **(A)**	Power compressor absorbed, using a conventional heat pump **(B)**	Compression of two circuits (cascade) Coefficient **α** **(Γ)**	Power of 1st compressor KW **(Δ)**	$C.O.P_{\theta o\lambda} = \frac{\alpha + c.o.p_{\cdot\theta 1}}{1+\alpha}$ **(E)**
3,3	4,85	1	3,75	2,15
Heat output in the house from both circuits (KW) **(Z)**	Absorbed compressor's Power For two refrigerant circuits (KW) **(H)** (cascade)	Cost of operation per KWh using the electricity price 0,25 €/kwh Case **B** (€/h) **(Θ)**	Operation Cost Case **H** (€/h) (cascade) **(I)**	**Difference I-Θ (€/h)** **(K)**
16,125	7,5	1,2125	1,875	0,6625 Namely increased operation cost 0,6625 €/h