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CASCADE HEAT PUMP DRYER PERFORMANCE IMPROVEMENT USING A SOLAR COLLECTOR

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ABSTRACT

Heat pump cycles are used in heating, drying, and other applications, and have recently seen greater use in the drying of clothes and food stuffs. Driers using the heat pump cycle are limited in that their performance changes in environments with a low ambient temperature such as winter. Researchers are working to resolve this downside, and the most prevalent solution is to use additional heat sources, such as solar, geothermal, and recovered heat. This paper implemented the cascade cycle with solar radiation as an additional external heat source, and conducted performance analyses of the drier at different ambient temperatures. Results indicated that when a cascade cycle combined with a solar collector is used, operational performance at low temperatures is greatly improved.

Keywords: heat pump dryer, solar collector, cascade cycle, refrigerant.

INTRODUCTION

Due to the cooling cycle's high efficiency, it is used in refrigerators, freezers, air conditioners, and other electronics, as well as in industrial processes. The heat pump cycle, which gains heat unlike the cooling cycle, is used in many applications such as heating and drying, and its use in drying clothes and food stuffs has been increasing.

Among the many methods used to dry clothes and food, using high-temperature air is the most representative approach. Using an electric heater, in particular, is structurally simple and inexpensive to implement, but has low efficiency as heat of the air is lost when emitted into the surroundings. An alternative to the heater method is to apply the heat pump cycle, but this method is complex to implement and expensive. However, it possesses higher efficiency than the electric heater, and as a result, is used in large scale facilities.

The heat pump drier is generally different from other heating/cooling devices in that the evaporator and condenser are placed within the drier. The air drying method using an electric heater expels the hot humid air that has already flowed past the dried goods. However, the heat pump method passes the humid air through the evaporator to reduce the air's temperature and humidity. The evaporator absorbs the heat from the hot humid air and sends that heat back into the drier through the condenser. Using this process, the heat pump drier exhibits high efficiency, but in environments with a low ambient external temperature, the performance deteriorates drastically.

Much research has been performed with the objective of increasing the performance of heat pump driers. A significant portion of past research focused on changing the structure in order to enhance performance. Notable contributions were made by Prasertsan *et al*. [2], who studied the effect of operating environment and conditions on heat pump driers, and Bivens *et al*. [3], who discussed the effects of applying an internal heat exchanger to the heat pump drier. Additionally, Cho *et al.* [4] proved that performance increases when a heat exchanger is included. Recent research is focused on the applications of external heat sources such as solar radiation, geothermal heat, and recovered heat [5, 6] to not only enhance the efficiency of heat pump heaters, but also to enhance performance in low ambient temperatures that can drastically degenerate the performance of heat pumps. Baek *et al*. [7, 8] demonstrated that attaching a solar collector to the heat pump helps improve performance. Mohanraj [9] experimentally confirmed using copra that in a high temperature, high humidity environment, drying performance is increased with the inclusion of solar radiation.

Hence, this paper aims to improve system efficiency by enhancing drier performance at low temperatures. A cascade cycle, a type of heat pump cycle, was implemented with a solar collector as an external heat source, and the change in performance was analyzed using the Engineering Equation Solver (EES).

Analysis method and conditions

To enhance operating performance at low ambient temperatures and increase COP efficiency while using the binary refrigerant cascade heat pump cycle, EES was used to analyze the cycle. Figure-1 shows the overall flow diagram of a cascade heat pump drier. The refrigerants, R134a-R410a and Ammonia-Carbon dioxide, were placed in two different cases and tested for performance changes caused by ambient temperatures. The external ambient temperature was assumed to be between 50°C and 0°C, and the temperature of the drier's insides were assumed to be 30-60°C. The condenser is placed inside the drier such that it exchanges heat with the internal air, whereas the evaporator is affixed outside, causing it to transfer heat to the ambient air. Also, the cascade heat exchanger acts as the evaporator of the high pressure cycle and the condenser of the low pressure cycle, sending heat absorbed from the low pressure cycle straight to the high pressure cycle. Additionally, a solar collector was used to inject further heat into the cascade heat pump cycle, and the change in the cycle due to the addition of the extra heat was studied.

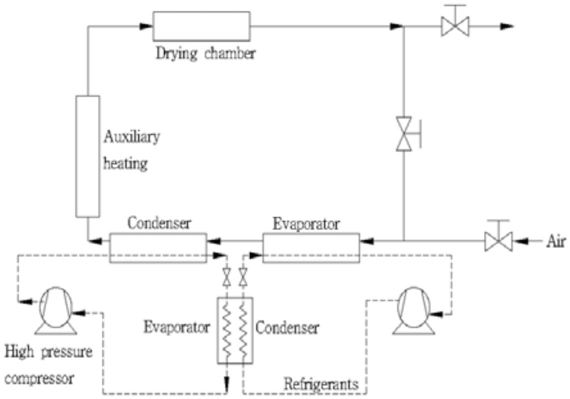

Figure-1. Schematic of cascade heat pump dryer.

RESULTS AND DISCUSSIONS

Cascade heat pump cycle analysis using R134a-R410a

Analysis of the cascade heat pump cycle with R134a-R410a was carried out. Figure-2 shows the heat emitted by the condenser depending on the ambient and internal temperatures. When the internal temperature is 30°C and the ambient temperature is -50°C, a total of 6.5kW of heat is emitted, which is reduced to 4.5kW when the ambient temperature is raised to 0°C. When the internal temperature is 60°C and the ambient temperature is -50°C, a total of 8.0kW of heat is released, which falls to 5.5kW when the ambient temperature is raised to 0°C. This shows the relationship where raising the ambient and internal temperature reduces and increases heat radiation, respectively.

Figure-3 illustrates the changes in compression work with respect to ambient and internal temperatures. Compression work is the integral of work performed during the whole cycle. When the internal temperature is 30°C and the ambient temperature is -50°C, compression work is 3.0 kW, and raising the ambient temperature to 0°C, compression work is measured to 0.9kW, indicating that raising the ambient temperature reduces the amount of compression work. Additionally, setting the ambient temperature to -50°C and the internal temperature to 60°C, compression work is approximately 4.4kW, but this Figure decreases to 3.0kW when the internal temperature is lowered to 30°C, demonstrating compression work increases along with the internal temperature. This is due to the increase in vaporization pressure that occurs when the ambient temperature is increased, reducing the load of the condenser and reducing the necessary compression work, whereas increasing the internal temperature also increases the condensation pressure, and in turn, the compression work required.

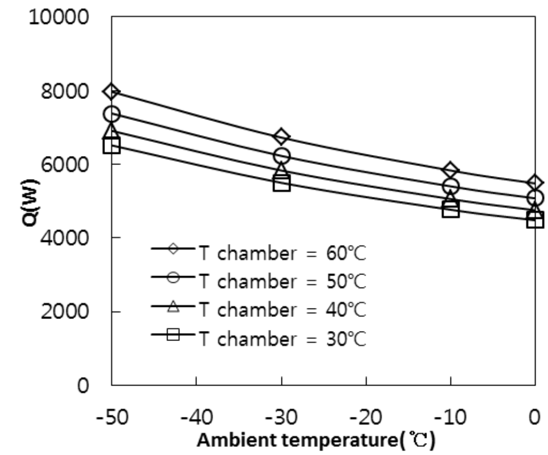

Figure-2. Variation of amount of heat release with ambient temperature

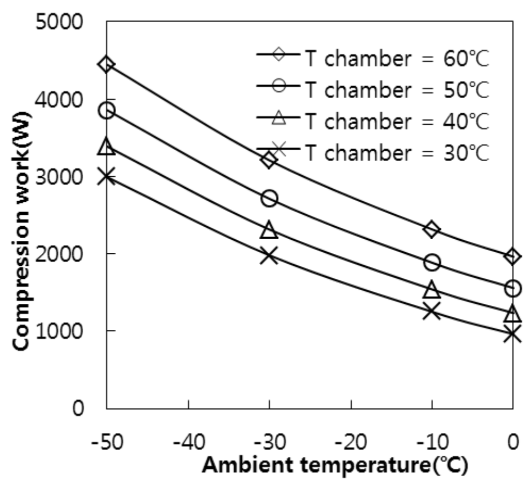

Figure-3. Variation of compression work with ambient temperature.

Figure-4 shows the change in COP with respect to the ambient and internal temperatures. The COP is approximately 2.2 when the internal temperature is set to 30°C, and the ambient is set at -50°C. Raising the ambient temperature also increases the COP, which reaches 4.6 at 0°C. Also, increasing the internal temperature causes the COP to decrease. The COP is approximately 1.8 at an internal temperature of 60°C and an ambient temperature of -50°C, which rises to 2.8 when the ambient temperature is increased to 0°C. This increase in COP is due to the reduction of the condenser load at higher ambient temperatures, whereas the inverse is true when the compressor load is increased by increasing the internal temperature.

A cost analysis was performed to investigate the cost required by the cascade heat pump system. Figure-5 shows the relationship between the ambient temperature and total cost. The internal temperature was assumed to be 60°C. The overall cost increases as the ambient

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temperature decreases, and this is related to the change in COP. When the COP is at its lowest point when the ambient temperature is -50°C, the cost is at its highest, and the two values have an inverse relationship.

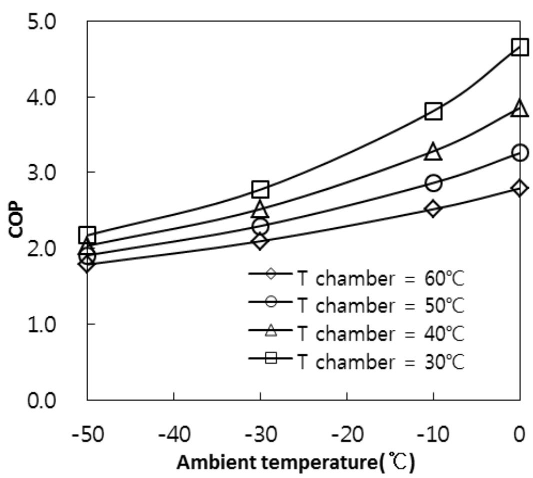

Figure-4. Variation of COP with ambient temperature.

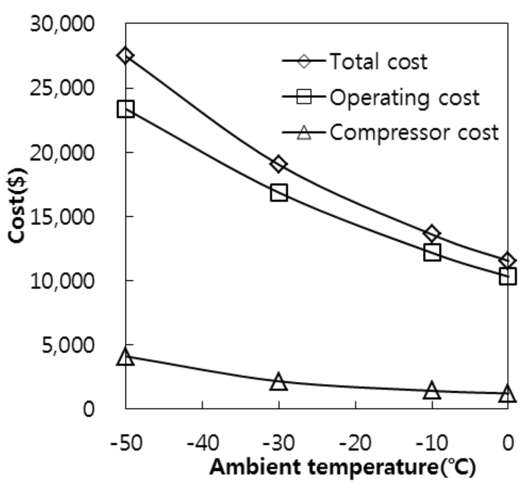

Figure-5. Variation of COST with ambient temperature.

Cascade heat pump cycle analysis using ammonia-carbon dioxide

The previous section analyzed the cascade heat pump cycle using R134a and R410a. Using it as a basis, the cascade heat pump cycle was analyzed, only this time using ammonia and carbon dioxide. Figure-6 shows the heat radiated with respect to the ambient temperature and internal temperature. The overall trend is the same as when R134a and R410a were used. Heat radiation values when the ambient temperature is 0°C are similar to those measured when R134a-R410a was used, but the amount of heat released increased, and as such, at an ambient temperature of -50°C, heat radiation increased by 6% more than when R134a-R410a was used.

Figure-7 shows the compression work with respect to the internal and ambient temperature. Again, similar to the previous case, raising the ambient temperature decreases the compression work. When the internal temperature is 30°C and the ambient temperature is -50°C, the compression work is 3.7kW, but once the ambient temperature is raised to 0°C, compression work falls to approximately 1.0kW, which is 0.7kW and 0.1kW greater than both tests performed in the previous case. The compression work is largest at 5.0kW, which is 0.6kW higher than the previous case, when the internal temperature is set to 60°C, and the ambient temperature is -50°C. These results corroborate that ammonia and carbon dioxide place more strain on the compressor than the R134a-R410a combination.

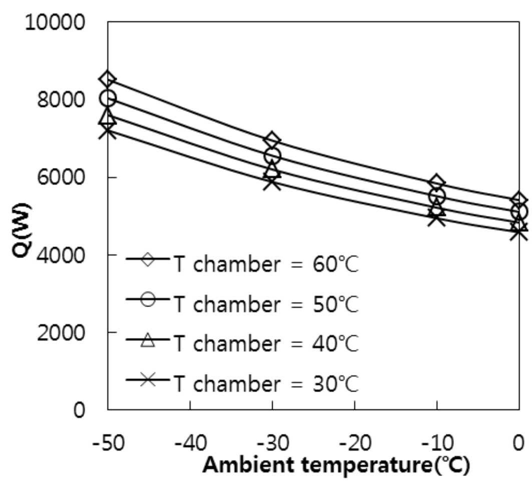

Figure-6. Variation of amount of heat release with ambient temperature.

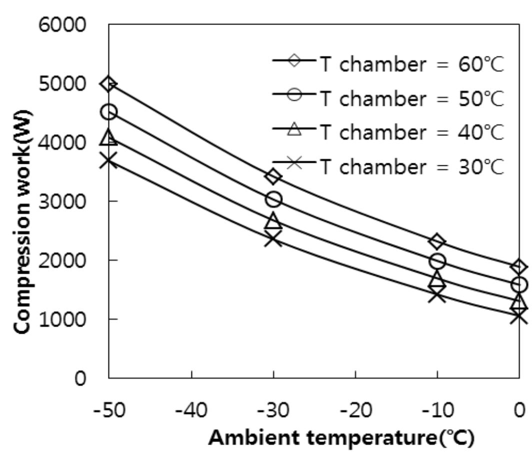

Figure-7. Variation of compression work with ambient temperature.

Figure-8 shows the change in COP with respect to the internal and ambient temperatures. The COP is approximately 1.9, 0.2 lower than the previous case, when the internal temperature is set to 30°C, and the ambient

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temperature is -50°C. COP increases as the ambient temperature rises, and when the ambient temperature reaches 0°C¸COP is 4.3, a lower efficiency compared to the previous case. All other trends were identical, and overall COP was measured to be lower than R134a-R410a. COP values were lower even when heat radiation increased because the increase of compression work was larger than that of the heat radiation, reducing the efficiency.

Figure-9 shows the cost with respect to ambient temperature. The cost is highest when ambient temperature is -50°C, costing a total of around $27, 566, which is $86 more than when R134a-R410a was used. Also, when the temperature is -50°C, the operating costs for the compressor are $1,310, which is much lower than the $4, 111 for R134a-R410a, indicating that the compressor load is much lower. The COP is lower than the previous case by approximately 5%, with only a 1% cost increase, demonstrating that ammonia and carbon dioxide are more cost efficient than when R134a-R410a was used.

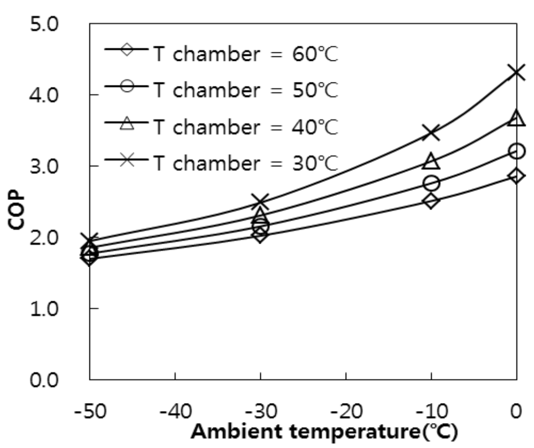

Figure-8. Variation of COP with ambient temperature.

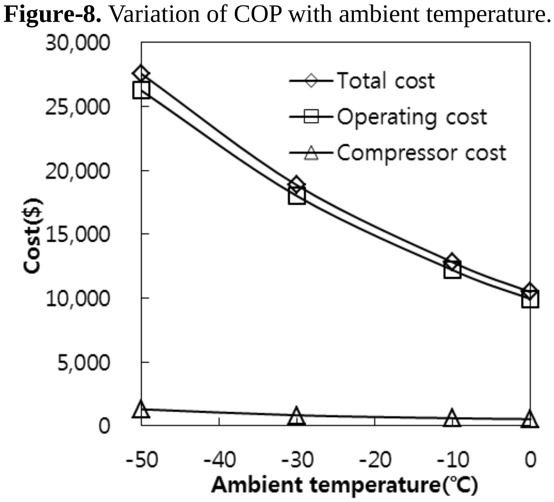

Figure-9. Variation of COST with ambient temperature.

Cascade heat pump cycle analysis using a solar collector, subcooling, and superheating

The heat pump cycle was analyzed with the assumption that injecting additional heat using a solar collector would reduce the temperature difference of the cascade heat exchanger. Figure-10 shows the change in COP with respect to temperature differences in the high pressure and low pressure cycles of the cascade heat exchanger. When the solar collector is not considered, the difference is 10°C, and the maximum COP is 2.2. When additional heat is injected using the solar collector, the temperature difference decreases, and the maximum COP rises to 2.4. As a result, the solar collector was shown to improve efficiency by approximately 10%.

Figure-11 shows the change in heat radiation with respect to the temperature difference of the cascade heat exchanger. Heat radiation increases as the internal temperature rises, and the additional heat provided by the solar collector does not affect the heat release rate of the condenser much. At internal temperatures of 60°C, the heat release rate rises from approximately 2.63kW to 2.65kW, an increase of 0.02kW, and when the internal temperature is 40°C, the heat release rate rises from approximately 2.27kW to 2.29kW, or an increase of 0.02kW; in other words, the effect is less than 1% of the total heat.

Figure-12 shows the change in COP due to subcooling. It was assumed that temperature difference of the heat exchanger with a solar collector attached was 0°C, and that there was no superheating. As subcooling increases, COP also increases, and this is due to the corresponding increase in heat release from the condenser. Without subcooling, COP reaches a maximum of 2.4, but with subcooling, a maximum COP value of 2.6 is measured at 20°C, which is a 10% enhancement in efficiency.

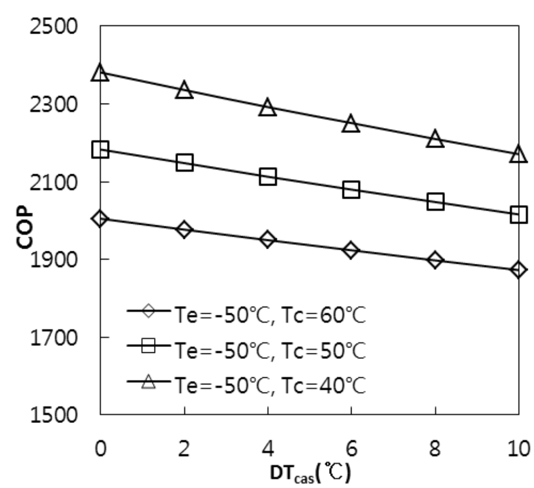

Figure-10. Variation of COP with temperature difference of cascade heat exchanger.

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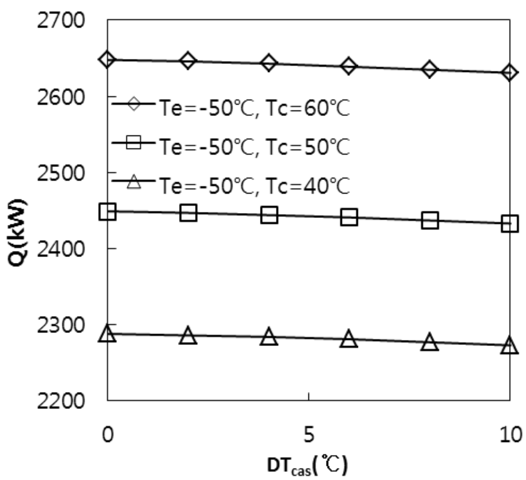

Figure-11. Variation of amount of heat release with temperature difference of cascade heat exchanger.

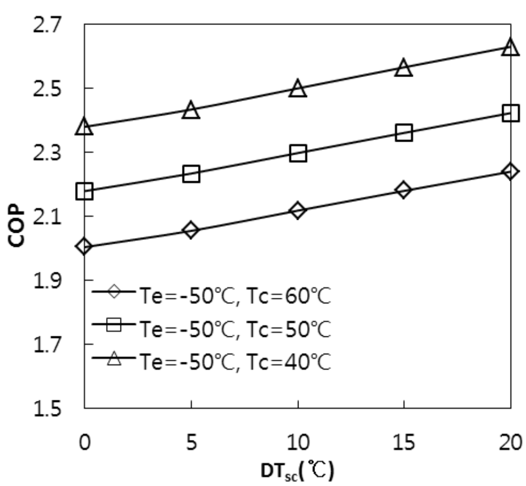

Figure-12. Variation of COP with subcooling.

Figure-13 shows the change in COP with respect to superheating effects. When the internal temperature is 40°C, the superheating increases while COP decreases. When the internal temperature is 50°C, changes in COP are negligible. When the internal temperature is set to 60°C¸ the COP rises, but the overall COP only changes by approximately within 0.5%, meaning that performance enhancements due to superheating are minimal. Increasing the superheating degree decreases the compression work needed and the heat release, but the larger the load placed on the overall system, the decrease in compression work becomes larger than the decrease in heat release, which increases the COP. On the other hand, a lesser load means a larger heat release value and a decrease in COP.

Figure-14 shows the P-h diagram with solar collector when the superheating and subcooling degrees are 20°C, the temperature difference is 0°C¸the internal temperature is 60°C, and the ambient temperature is -50°C. Heat radiation is 2.6kW, compression work is 1.2kW, and COP is approximately 2.2, which is a 19% increase over the COP (1.9) of the cascade heat pump cycle. By manipulating not only the solar collector, but also the degree of superheating and subcooling, a highly efficient cascade heat pump cycle can be designed.

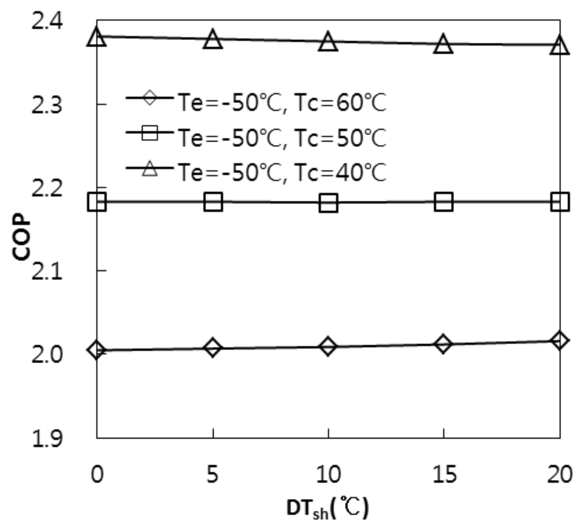

Figure-13. Variation of COP with superheating.

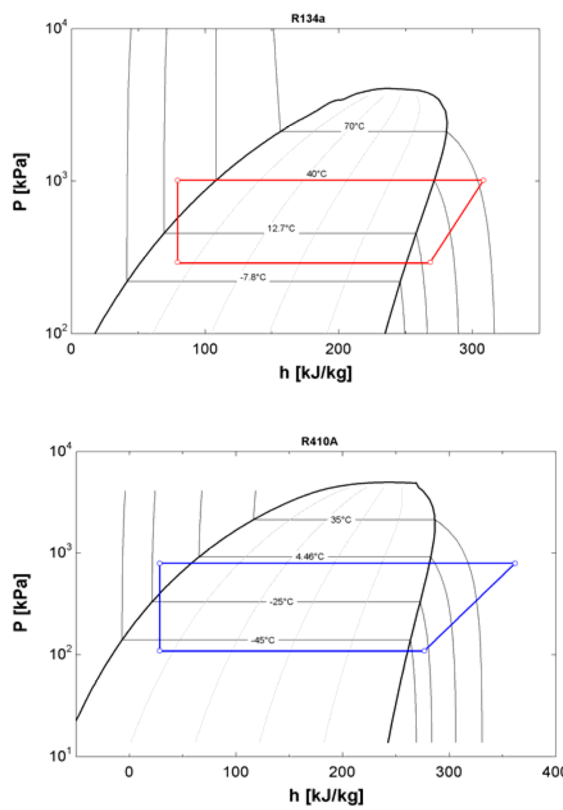

Figure-14. P-h diagram with solar collector when the superheating and subcooling.

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CONCLUSIONS

This paper performed an analysis of a cascade heat pump cycle with a solar collector attached in order to enhance drier performance in low temperature environments, and the following conclusions were reached.

a) A cascade heat pump using R134a-R410a at an ambient temperature of -50°C has a COP of approximately 1.8, exhibiting high efficiency compared to a standard heat pump cycle. When the ambient temperature reaches 0°C, COP rises to 2.8, which demonstrates that it can enhance operating performance in low temperature environments.
b) A cascade heat pump cycle using ammonia and carbon dioxide, given an ambient temperature of -50°C, resulted in a COP of 1.7, which is 0.1 lower than the R134a-R410a test case. However, ammonia and carbon dioxide released more heat by over a 6% difference. Hence in situations that require higher heat release, ammonia and carbon dioxide is more efficient.
c) Attaching the solar collector to the cascade heat pump drier increases the COP by around 10%. This result indicates that the use of external heat sources can be a vital factor in improving cycle efficiency. Additionally, a 9% increase in the COP value can be produced through optimization of subcooling and superheating degrees.

More experimental research with driers outfitted with cascade heat pump cycles and solar collectors is deemed necessary.

ACKNOWLEDGEMENTS

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