2014

The Effects of Gas Cooler Inlet Pressure on System Performance in Heat Pump Tumble Dryers

Serkan Erdem
Yildiz Technical University, Turkey, serdem@yildiz.edu.tr

Cenk Onan
Yildiz Technical University, Turkey, conan@yildiz.edu.tr

Hasan Alpay Heperkan
Yildiz Technical University, Turkey, heperkan@yildiz.edu.tr

Derya Burcu Özkan
Yildiz Technical University, Turkey, tumer@yildiz.edu.tr

The Effects of Gas Cooler Inlet Pressure on System Performance in Heat Pump Tumble Dryers

Serkan ERDEM[1]*, Cenk ONAN[2], Hasan H. HEPERKAN[3], Derya B. OZKAN[4]

[1]Yildiz Technical University, Department of Mechanical Engineering, Istanbul, Turkey
Phone: 0090 212 383 29 16, Fax: 0090 212 261 66 59, E-mail: serdem@yildiz.edu.tr

[2]Yildiz Technical University, Department of Mechanical Engineering, Istanbul, Turkey
Phone: 0090 212 383 29 16, Fax: 0090 212 261 66 59, E-mail: conan@yildiz.edu.tr

[3]Yildiz Technical University, Department of Mechanical Engineering, Istanbul, Turkey
Phone: 0090 212 383 28 11, Fax: 0090 212 261 66 59, E-mail: heperkan@yildiz.edu.tr

[4]Yildiz Technical University, Department of Mechanical Engineering, Istanbul, Turkey
Phone: 0090 212 383 29 11, Fax: 0090 212 261 66 59, E-mail: tumer@yildiz.edu.tr

* Corresponding Author

ABSTRACT

Heat pumps working with CO_2 as a refrigerant have low energy consumptions depending on selected application areas and operating conditions. The use of CO_2 in heat pump dryers is feasible if operating temperatures are appropriate. In heat pump dryers working with CO_2 according to the transcritical cycle, one of the most important operating conditions is optimum gas cooler inlet pressure, which gives the maximum coefficient of performance (COP). In this study, a model was developed by using MATLAB software for heat pump tumble dryer working with CO_2. The model was validated by experimental data taken from existing literature. Then, COP, moisture extraction rate (MER), and specific moisture extraction rate (SMER) were found by running the model at different gas cooler inlet pressures (80–140 bar). All results were calculated in the same geometry for evaporator, gas cooler, and compressor. Thus, effects on the results of variation of the geometrical features were eliminated. Optimum gas cooler inlet pressure was determined with data input to the model as 100 bar for the system. In the optimum gas cooler inlet pressure working condition, SMER increased 24% and 12% by comparison with 80 bar and 140 bar gas cooler inlet pressure, respectively.

1. INTRODUCTION

Use of CO_2 in the heat pump dryer reduces damage to the environment, because CO_2 is natural and harmless to the environment with its appropriate thermodynamic properties. Its use also can reduce the energy consumption and drying time. However, the use of CO_2 in the dryer is not enough for the realization of all of these positive effects. In the heat pumps work according to the transcritical cycle with CO_2, heat rejection occurs in gas cooler working in the supercritical region. In the supercritical region, pressure and temperature are independent of each other. Therefore, there is not a linear relation between the COP and the pressure, which makes it important to determine the optimum gas cooler inlet pressure that gives the maximum COP.

Kauf (1999) developed a simulation model to obtain the optimum gas cooler inlet pressure; then he established a control function for the optimum gas cooler inlet pressure depending on the ambient temperature or refrigerant temperature at the outlet of gas cooler. This function was used to adjust the high pressure so that the system could be run with maximum COP.

Liao *et al*. (2000) developed a simulation model to optimize the COP of transcritical carbon dioxide air-conditioning cycles by determining the optimum gas cooler inlet pressure. The isentropic efficiency of the compressor was taken into consideration. It was revealed that the values of the optimal heat rejection pressure mainly depended on the outlet temperature of the gas cooler, the evaporation temperature, and the performance of the compressor.

Chen and Gu (2005) primarily investigated the effectiveness of the internal heat exchanger for the CO_2 system at cooling mode and developed a correlation of optimum high pressure based on the simulation data. They reported that evaporating temperature has little influence on optimum gas cooler inlet pressure.

Aprea and Maiorino (2009) presented experimental research on working optimization for a residential split air-conditioning system by varying the heat rejection pressure and ambient temperature respectively. They suggested that the heat rejection pressure optimization was a convenient method to improve the performance of a carbon dioxide split system.

Özgür *et al.* (2009) obtained the optimum gas cooler inlet pressure as a function of evaporation temperature of CO_2 and outlet temperature of CO_2 following the gas cooler in their numerical study. They reported that the evaporation temperature interval was wider than the recent literature works.

Zhang *et al*. (2010) conducted the experimental and simulation researches to investigate the relationships between optimum heat rejection pressure and other related operating parameters for a transcritical CO_2 heat pump system with two throttle valves. They reported that the optimal heat rejection pressure mainly depends on the refrigerant outlet temperature of gas cooler, whereas the evaporating temperature and the performance of the given compressor have smaller effect on the optimum heat rejection pressure.

Cecchinato *et al*. (2010) addressed the optimal energy efficiency and high-cycle pressure problem in single-stage refrigerating carbon dioxide vapor compressor units operating in transcritical conditions. The analysis showed a strong sensitivity of the gas cooler outlet temperature from the secondary fluid temperature, from its capacity rate, and from the heat exchanger geometry.

In this study, a simulation model was developed for heat pump laundry dryer works with CO_2 transcritical cycle. The model can determine the COP, MER, SMER, drying time, and energy consumption when the heat exchangers' geometry, specifications of compressor-drum-fan, and ambient conditions are input to the model. The model was validated by the appropriate experimental data collected from literature. Then, the effects of the CO_2 inlet pressure into the gas cooler on COP, drying time, and energy consumption were investigated. The gas cooler inlet pressure was changed between 80–140 bar. In contrast to the literature studies, the effects of gas cooler inlet pressure on MER and SMER were presented.

2. HEAT PUMP DRYERS

As shown in Figure 1, heat pump dryers have two cycles: air cycle and refrigerant cycle. In the air cycle, air is heated in the gas cooler and is sent to the drum. Then, air gets moisture from the laundry and comes to the evaporator. Air leaves moisture on the evaporator's outside surface, and comes back to the gas cooler. The refrigerant side is a vapor compression cycle that uses CO_2 in this study.

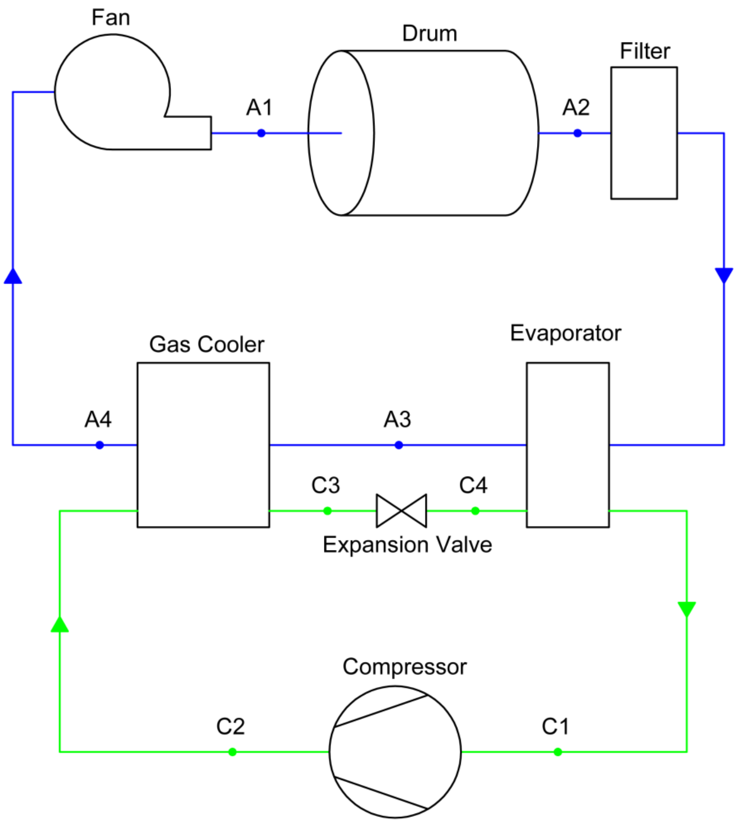

Figure 1: A schematic view of heat pump drying system

2.1 Model

To generate a heat pump drying system simulation model, all components shown in Figure 1 were modeled separately. Then, they were combined to work together. Thus, all components affect the others. Inputs and outputs of the model are shown in Table 1.

Table 1: Inputs and outputs of the heat pump dryer model

Inputs	Outputs
Gas cooler geometry	Coefficient of performance
Evaporator geometry	Moisture extraction rate
Compressor specifications	Specific moisture extraction rate
Drum specifications	Drying time
Fan specifications	Energy consumption
Ambient air specifications	Airside conditions of every point of cycle
Operating parameters	CO_2 side conditions of every point of cycle

The modeling study was made by using MATLAB R2011b software. To determine thermophysical properties of the air and CO_2 in the calculations, Refprop V7 software was used. The properties of water, copper, stainless steel, and aluminum that could be used as pipe and fin material were determined using EES V9 software.

Optimum operating parameters and heat exchanger geometries can be determined by using the model in design stage of the heat pump laundry dryers. Thus, the design stage can be accelerated and operating costs can be reduced by producing more effective dryers.

2.2 Validation of Model

For validation of the general dryer model, the experimental study of Klöcker *et al*. (2001, 2002) was taken into consideration.

Among the criteria used for comparison, coefficient of performance (COP), moisture extraction rate (MER), and specific moisture extraction rate (SMER) are expressed with equations (1), (4), and (5), respectively.

$$COP = \frac{\dot{Q}_{gc}}{\dot{W}_c} \tag{1}$$

$$\dot{Q}_{gc} = \dot{m}_r(h_{C2} - h_{C3}) \tag{2}$$

$$\dot{W}_c = \dot{m}_r(h_{C2} - h_{C1}) \tag{3}$$

$$MER = \dot{m}_a(\omega_{A2} - \omega_{A1}) \tag{4}$$

$$SMER = \frac{MER}{\dot{W}_c + \dot{W}_f} \tag{5}$$

$$\dot{W}_f = \dot{m}_a(h_{A1} - h_{A4}) \tag{6}$$

Sarkar *et al*. (2006a, 2006b) validated their steady-state simulation model with the experimental results at the 50th min. of Klöcker *et al*. (2001, 2002). In this study, these 50th min. experimental results were used for validation. The results of Klöcker *et al*. (2001, 2002) are given in Table 2 by comparing the results obtained from dryer model. Deviations are calculated with equation (7).

$$\text{Deviation} = \frac{|\text{Experimental Results} - \text{Model Results}|}{\text{Experimental Results}} \times 100 \tag{7}$$

Table 2: Comparison of the experimental study by Klöcker *et al*. (2001, 2002) and results of the model

		Experimental Results Klöcker *et al*. (2001, 2002)	**Model Results**	**Deviation (%)**
Cooling Load	kW	10.15	10.7	5.4
Heating Load	kW	12	13.0	8.3
Compressor Power	kW	1.85	2.28	23.2
COP	-	6.5	5.70	12.3
MER	kg/h	5	5.90	18.0
SMER	kg/kWh	2.05	1.99	2.9

3. THE EFFECTS OF GAS COOLER INLET PRESSURE

In subcritical cycles, as the pressure of the cooling fluid in the condenser decreases, COP increases. However, in the heat rejection in the supercritical region, the pressure and temperature are independent from each other contrary to the wet steam region. For this reason, there is no linear relation between COP and gas cooler. The model developed according to this data was operated with different gas cooler inlet pressures and its effect on the system performance was determined.

When the gas cooler inlet pressure increased from 80 bar to 140 bar, gas cooler inlet CO_2 temperature increased. As seen in Figure 2, temperature differences of CO_2 side between inlet and outlet of gas cooler also increased. In the same way, air side temperature differences between inlet and outlet of gas cooler increased (Figure 3).

These temperature difference increases yield increases in heat transfers at the gas cooler. When the gas cooler inlet pressure is increased, compressor power consumption increased because compression ratio increased. CO_2 side was shown in the P-h diagram depending on the model results in Figure 4.

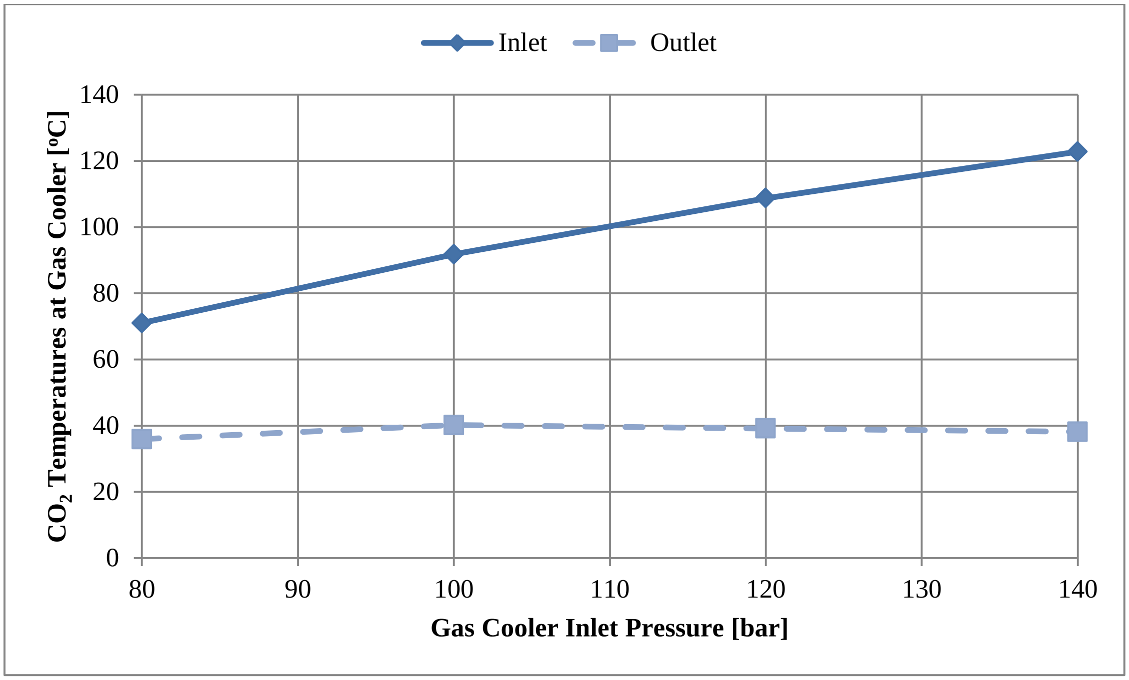

Figure 2: CO_2 side temperatures of gas cooler depending on gas cooler inlet pressure

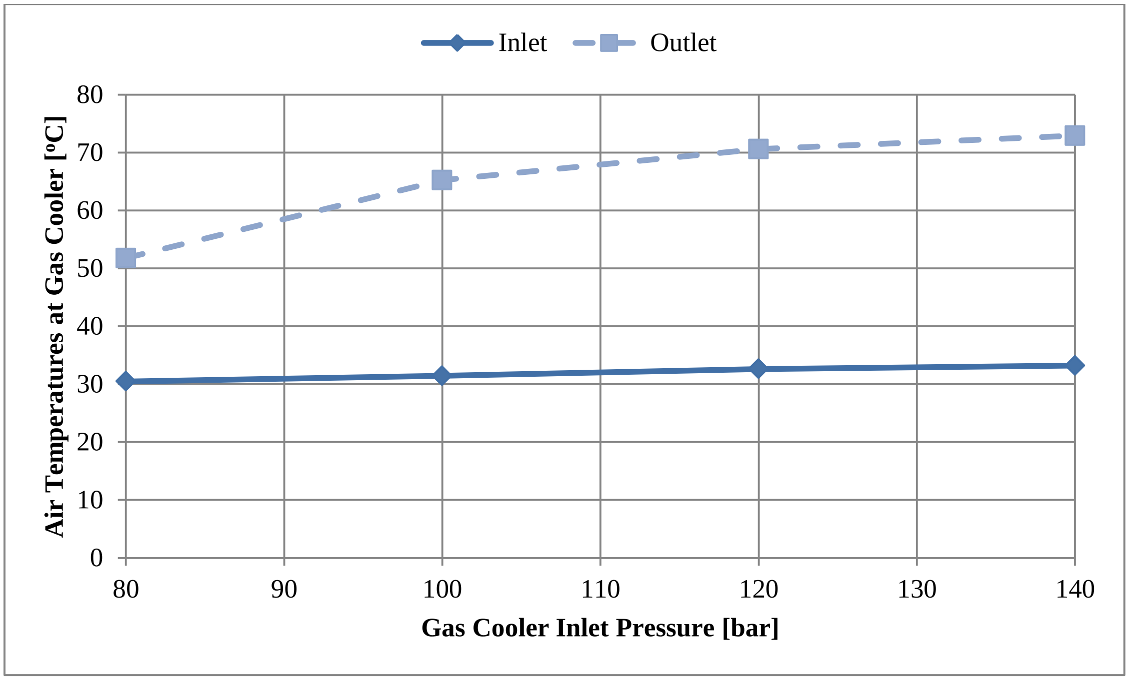

Figure 3: Air side temperatures of gas cooler depending on gas cooler inlet pressure

Using Figure 4, heat transfer in the gas cooler, compressor power, and COP were shown in Figure 5. As seen in Figure 5, maximum COP occurred at about 100 bar, which was determined optimum gas cooler inlet pressure.

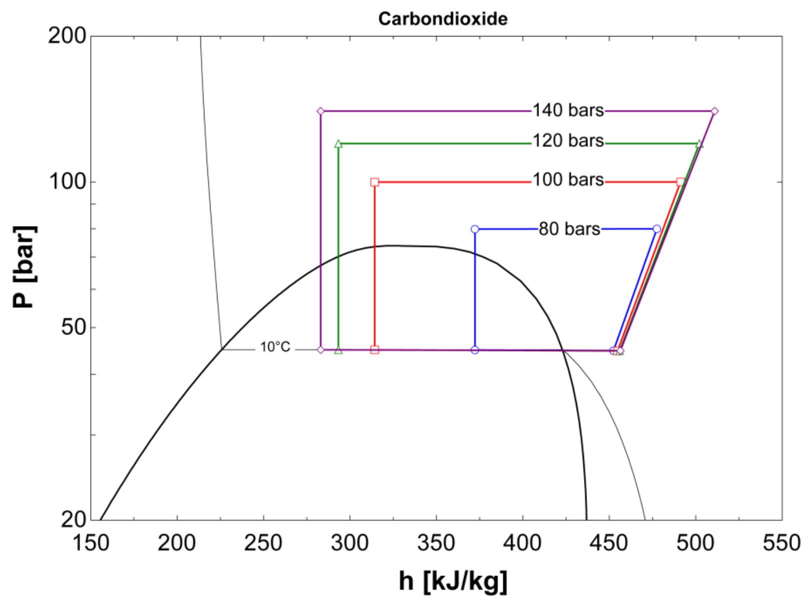

Figure 4: Heat pump dryer's CO_2 side in P-h diagram depending on gas cooler inlet pressure

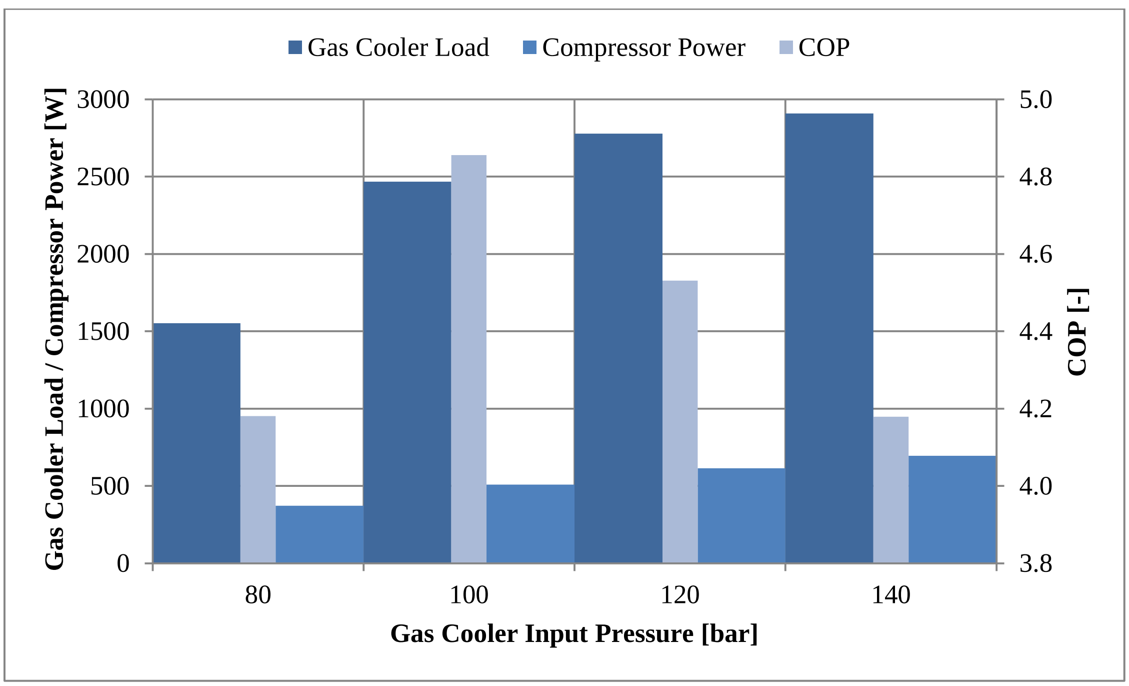

Figure 5: Gas cooler load / compressor power and COP of heat pump dryer depending on gas cooler inlet pressure

Drum inlet air temperature increased with increasing gas cooler inlet temperature. Whereas, drum inlet air relative humidity was decreased with increasing gas cooler inlet temperature as seen in Figure 6. Thus, more dry and hot air was able to be sent to the drum. The dehumidification capability of this air was higher. So MER increased with increasing gas cooler inlet pressure as seen in Figure 7. Only increasing rate of MER decreased above 100 bar.

Maximum SMER occurred at about 100 bar gas cooler inlet pressure depending on MER and compressor power consumption.

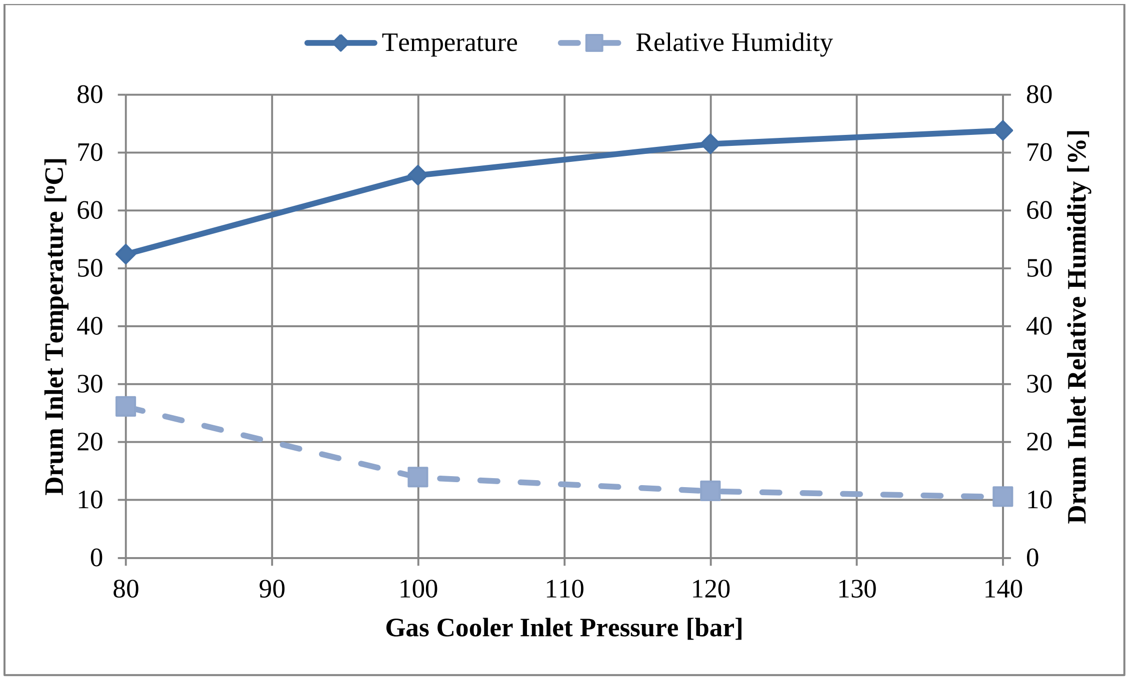

Figure 6: Temperatures and relative humidity of drum inlet air depending on gas cooler inlet pressure

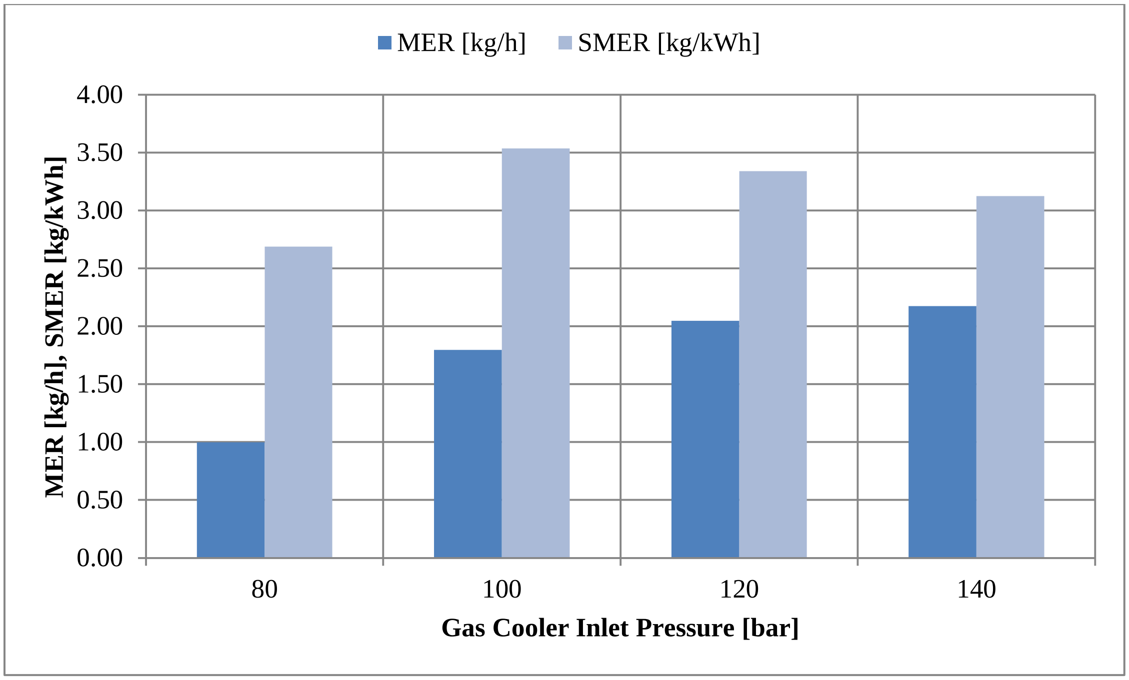

Figure 7: MER and SMER of heat pump dryer depending on gas cooler inlet pressure

6. CONCLUSIONS

CO_2 seems suitable for using in heat pump laundry dryer because of appropriate operating parameters and environmentally friendly properties. In this study, a heat pump laundry dryer simulation model working with CO_2 was developed. The model was validated with experimental results obtained from literature. The effects of gas cooler inlet pressure were presented. Under these conditions, gas cooler inlet pressure was changed between 80 bar and 140 bar.

- Optimum gas cooler inlet pressure was determined as 100 bar depending on the data input to the model.
- COP increased 14% at 100 bar when we compared the results with the 80 bar gas cooler inlet pressure. The increase in COP was also 14% at 100 bar when we compared the results with the 140 bar gas cooler inlet pressure, which was the end of range.
- MER increased 44% at 100 bar when we compared the results with the 80 bar gas cooler inlet pressure. At 140 bar gas cooler inlet pressure working condition, MER increased 21% when we compared the results with the optimum gas cooler working pressure because MER was increased with the gas cooler inlet pressure.
- In the optimum gas cooler inlet pressure working condition, SMER increased 24% and 12% when we compared the results with the 80 bar and 140 bar gas cooler inlet pressure, respectively.

Depending on these results, operating heat pump dryers at optimum gas cooler inlet pressure will be able to increase the efficiency of the system. Also, operating costs can be reduced depending on the maximum SMER at optimum gas cooler inlet pressure.

NOMENCLATURE

COP	coefficient of performance	(-)
h	enthalpy	(kJ/kg)
$\dot{m}$	mass flow rate	(kg/h)
MER	moisture extraction rate	(kg/h)
$\dot{Q}$	heat transfer rate	(W)
SMER	specific moisture extraction rate	(kg/kWh)
T	temperature	(^{o}C)
W	power	(W)
ω	absolute humidity for air	(kg_w/kg_{da})

Subscript

a	air
A	air cycle
C	CO_2 cycle
c	compressor
f	fan
gc	gas cooler
r	refrigerant
sat	saturation

REFERENCES

Aprea, C., Maiorino, A., 2009, Heat rejection pressure optimization for a carbon dioxide split system: An experimental study, *Appl. Energy*, 86, 11:2373–2380.

Cecchinato, L., Corradi, M., Minetto, S., 2010, A critical approach to the determination of optimal heat rejection pressure in transcritical systems, *Appl. Therm. Eng.*, 30, 13:1812–1823.

Chen, Y., Gu, J., 2005, The optimum high pressure for CO_2 transcritical refrigeration systems with internal heat exchangers, *Int. J. Refrig.*, 28, 8:1238–1249.

Kauf, F., 1999, Determination of the optimum high pressure for transcritical CO_2-refrigeration cycles, *Int. J. Therm. Sci.*, 38, 4:325–330.

Klöcker, K., Schmidt, E.L., Steimle, F., 2001, Carbon dioxide as a working fluid in drying heat pumps, *Int. J. Refrig.*, 24, 1:100–107.

Klöcker, K., Schmidt, E.L., Steimle, F., 2002, A Drying Heat Pump Using Carbon Dioxide as Working Fluid, *Dry. Technol.*, 20, 8:1659–1671.
Liao, S.M., Zhao, T.S., Jakobsen, A., 2000, A correlation of optimal heat rejection pressures in transcritical carbon dioxide cycles, *Appl. Therm. Eng.*, 20, 9:831–841.
Özgür, A.E., Bayrakçı, H.C., Akdağ, A.E., 2009, Kritik Nokta Üstü Çevrimli CO_2 Soğutma Sistemlerinde Optimum Gaz Soğutucu Basıncı - Yeni Bir Korelâsyon, *Isi Bilim. ve Tek. Dergisi/Journal Therm. Sci. Technol.*, 29, 2:23–28.
Sarkar, J., Bhattacharyya, S., Gopal, M.R., 2006a, Transcritical CO_2 Heat Pump Dryer: Part 1. Mathematical Model and Simulation, *Dry. Technol.*, 24, 12:1583–1591.
Sarkar, J., Bhattacharyya, S., Gopal, M.R., 2006b, Transcritical CO_2 Heat Pump Dryer: Part 2. Validation and Simulation Results, *Dry. Technol.*, 24, 12:1593–1600.
Zhang, X.P., Fan, X.W., Wang, F.K., Shen, H.G., 2010, Theoretical and experimental studies on optimum heat rejection pressure for a CO_2 heat pump system, *Appl. Therm. Eng.*, 30, 16:2537–2544.

ACKNOWLEDGEMENT

Thanks for Republic of Turkey Ministry of Science, Industry and Technology for their support.