EFFECTS OF CONTROL FACTORS ON OPERATING TEMPERATURES OF A MECHANICAL HEAT PUMP IN WASTE HEAT RECOVERY: Evaluation Using the Taguchi Method

by

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Original scientific paper
https://doi.org/10.2298/TSCI150323060M

In the present study, the operating temperatures of the mechanical heat pump in waste heat recovery were investigated to elucidate the effect of control parameters such as compressor speed, wastewater temperature and mass flow rate. The experimental trials were performed using the Taguchi L27 full factorial orthogonal array, and the results were optimized for compressor suction gas temperature, compressor discharge gas temperature, temperature difference of water entering and leaving the evaporator, temperature difference of water entering and leaving the condenser, evaporation temperature, and condensation temperature. Analysis of variance was conducted to determine the effect of the control factors on the operating temperatures of mechanical heat pump. The analysis results show that the wastewater temperature was the most significant factor on compressor suction gas temperature and discharge gas temperature. The compressor speed has shown a meaningful effect on the temperature difference of water entering and leaving from condenser. The nominal levels of control factors and the optimal temperatures were specified for the studied experimental parameters. Prediction models were developed for the operating temperatures through the Taguchi method and the operating temperatures were predicted with a mean squared error less than 12%.

Key words: *mechanical heat pump, heat recovery, waste heat, Taguchi method, operating temperatures*

Introduction

A heat pump is a device that can increase the temperature of a source of waste heat to a temperature at which the waste heat becomes useful. These machines are able to absorb thermal energy at a low-temperature level (heat source) in order to increase this energy to a higher temperature level (heat sink) and subsequently supply it for utilization (heating, hot water, or process heat). For maximum benefits from recovered energy, the heat recovery system should be physically close to the source of waste heat [1]. During the process, electrical power, primarily, is used for the compression of the refrigerant [2, 3]. Much industrial waste heat, in the form of sewage, cooling water or exhaust air, flows at temperatures of about 30 °C and liquid

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effluents at temperatures of between 10 and 60 °C are available at a range of industries. In particular, contaminated sewage, typically holding a certain quantity of heat, is the result of many washing and cleaning processes. As the discharge of these amounts of heat into the drainage system is either restricted or cost-intensive, the application of heat pumps in this case offers a double benefit: it reduces the sewage temperature and generates reusable heat [4]. Heat pumps have large potential contribution of reducing CO_2 emissions. It is possible to save up to 6% of the global CO_2 emissions by using heat pumps worldwide [5]. There are many studies in literature about heat pump applications. Heat pumps are widely used for upgrading ambient heat from sustainable sources, such as air, water, the ground and waste heat, to heating temperatures. There are many studies on ground, air, water and solar source heat pump systems or combined these systems in literature [6-11]. They can be used for residential and commercial space heating, cooling and water heating, refrigeration, and in industrial processes [12]. Especially in industrial processes, heat pumps are widely used. Baek *et al.* [13] designed and investigated the compression heat pump system by using wastewater from hotel with sauna. Huang *et al.* [14] analyzed a heat pump system in a high school bathroom. They reported that the system has good economic property for energy consuming and environment. Ajah *et al.* [15] studied on a simulation-based comparative analysis of the robustness of the most widely used heat pump technologies for low-temperature heat source. Also, they investigated a comparative, reliability, safety, and economic analysis of both technologies based on analysis and evaluation except for simulation. The high energy output was estimated at 923 TJ per year in the simulation and mechanical heat pump (MHP) contributes approximately 15% of the total energy demand. Therefore, they suggested that this heat pump can be combined with a natural gas-fired heater to provide the required heat and may also be used as a backup system. Pulat *et al.* [16] studied on thermodynamic analysis of a heat pump using waste heat obtained from dyeing process at textile industry in Turkey. The use of a heat pump to utilize the waste heat from a heat engine has been studied by Salah [17]. Studies about heat pumps used in drying applications were common in [18-21]. A new high temperature heat pump using water as refrigerant has been designed and built for testing on a laboratory test bench that reproduces the operating conditions of real-case industrial applications by Chamoun *et al.* [22].

The Taguchi method (TM) is a powerful tool for the design of high-quality systems. It provides a simple, efficient and systematic approach to designs for optimization of performance, quality and cost. The methodology is valuable when the design factors are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to sources of variation [23-25]. In recent years, rapidly increasing interest in the TM has led to numerous applications of the method in a worldwide range of industries, but the application of the TM for energy-based systems has been scant. For example, many studies have reported increases in heat pump performance, but there is a limited amount of research related to application of the TM to heat pump performance. Comakli *et al.* [26] investigated experimentally the effects of mixture concentrations, source temperature, flow rate of condenser cooling water, and air-flow rate in the cooling tower on the coefficient of performance (*COP*) and *Z* ex (exergetic efficiency) values of vapor compression heat pump systems. The TM was used to determine the efficiency of the chosen parameters on the system and optimum working conditions. Comakli *et al.* [27] specified the optimum working conditions for a heat pump system in which R22 and R404a refrigerant mixtures were used by using TM. The effects of control factors on the system performance (by TM) in a heat pump used for the recovery of waste heat were examined by Coskun *et al.* [28]. While Sivasakthivel *et al.* [29] determined the optimum working conditions of ground-sourced heat pumps for heating and cooling by using TM, a methodology proposed to optimize the solar collector area and ground heat exchanger length for achieving higher *COP* of solar assisted ground source heat pump system using TM and utility concept by Verma and Murugesan [30]. There are many studies by TM unlike heat pump applications. Such as, Bhoite *et al.* [31] employed TM in the thermal analysis of heat pipes. Lu *et al.* [32] examined to determine optimum design of natural circulation solar-water-heater by the TM. Pinar *et al.* [33] used TM to optimize the performance of the counter flow Rangue-Hilsch vortex tube system. Chen *et al.* [34] applied this method in the optimization of drying conditions for ginger oil.

The aim of this study is to determine the most significant parameters on operating temperatures of the MHP in waste heat recovery application. For this purpose, it was planned to heat a test room by using a MHP which absorbed heat from waste water and an experimental set-up was designed and constructed. Effects of three main parameters such as compressor speed, n_c, wastewater temperature, T_w, and mass flow rate, $\dot{m}_w$, were investigated on the operating temperatures such as compressor suction, T_1, and discharge, T_2, gas temperatures, evaporation, T_e, and condensation, T_c, temperature difference of water entering and leaving the evaporator, ΔT_{ew}, and condenser, ΔT_{cw}, as shown in fig. 1. The operating temperatures were estimated using TM to obtain optimum design conditions for waste heat recovery application of a MHP. Optimum levels of the control factors for operating temperatures of a MHP in waste heat recovery were determined. In design stage, it is important to know how the operating temperatures were affected by these control factors. So, control factors should be selected carefully design stage of the MHP in waste heat recovery. Results of this study will aid to design of a MHP in waste heat recovery application.

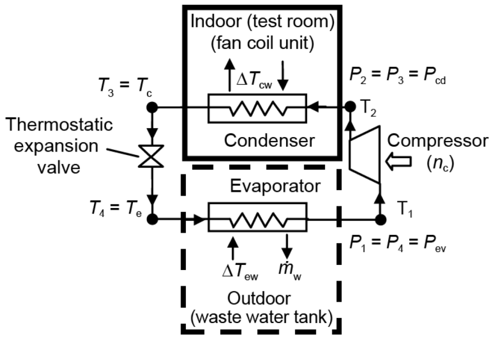


Figure 1. Representation of the control factors and operating temperatures on the MHP unit

Materials and method

Experimental study and analysis of the system

A heat pump uses a vapor compression cycle to take heat from a low-temperature source and raises its temperature to a useful level. In this study, the MHP was used for waste heat recovery application. Schematic diagram and picture of the experimental set-up are shown in fig. 2. It consists of a variable speed compressor, a condenser, an evaporator, a thermostatic expansion valve (TXV), a fan-coil unit, a wastewater tank, circulating pumps, and auxiliary equipment such as a receiver, dryer, sight glass, *etc.* Freon-134a was used as a refrigerant. Working principle of this system is as follows: the condensed liquid refrigerant from the condenser passes through the TXV directly into the evaporator where it gets evaporated by energy from wastewater (the wastewater is heated by electrical heater in the wastewater tank and pumped to the evaporator). Vaporized refrigerant passes through the compressor and finally the vapor at the high temperature and pressure is compressed to the condenser where it gets condensed. The energy rejected by the condenser is absorbed by water and sent to fan-coil unit [28]. During the experiments, the compressor speed was changed by changing frequency of compressor by means of frequency converter. Temperature and mass flow rate of the waste water was changed by electrical heater [11] and flow meter [10], respectively. In this study, compressor speed, wastewater temperature, and flow rate are chosen as control factors. These are most effective factors. Because refrigerant flow rate circulating in the MHP was performed by compressor and compressor speed affects heat transfer capacities of condenser and evaporator. Furthermore, changes of waste water temperature and flow rate also affect the outdoor unit *i. e.* evaporator. In a heat pump application, while the outdoor conditions change, indoor conditions are kept constant. So, water circulating between condenser and fan-coil unit was not chosen as control factor. Its flow rate was kept constant during the study.

During experimental study, K-type thermocouples were used to measure temperatures of water and refrigerant in the MHP system, while an anemometer was used to measure humidity and temperature of air. Pressure was measured with Bourdon type manometer. Voltage, current, and power factor, cos*φ,* were measured for calculating fan, pumps and compressor power consumptions by using clamp-on meter and cos*φ* meter. All data were recorded with in intervals of 15 seconds. All measurements are gathered by a data acquisition system and transferred to a personal computer. Details of the measurement devices employed are given in previous study conducted by Coskun *et al.* [28]. Experimental design was determined by using TM and the temperatures were measured. Each test was repeated three times and the temperature values given in tab. 2 are the arithmetic means of the temperature measurements. The obtained experimental data were analyzed in Minitab 16.0 software.

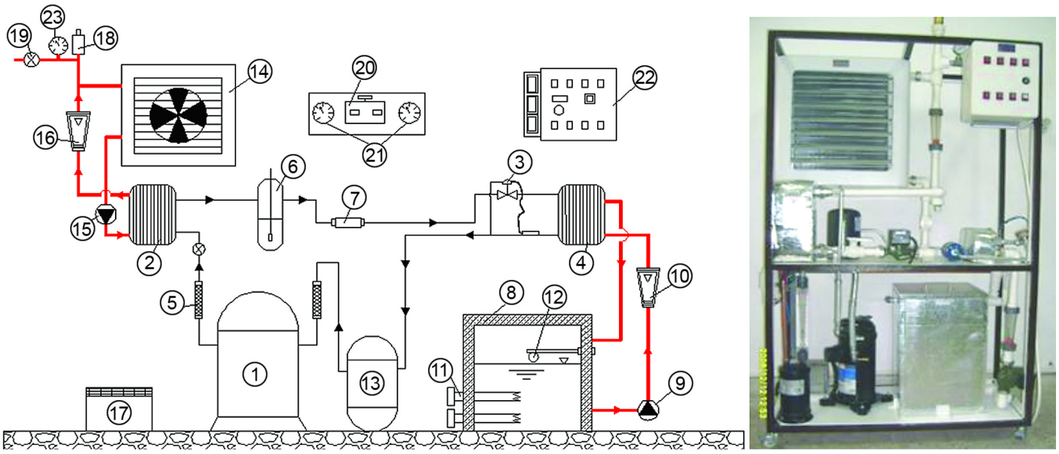


Figure 2. Schematic diagram and picture of the experimental set-up; *1 – compressor, 2 – plate heat exchanger (condenser), 3 – TXV, 4 – plate heat exchanger (evaporator), 5 – vibration absorber, 6 – receiver, 7 – dryer, 8 – wastewater tank, 9 – pump 1, 10 – flow meter 1, 11 – electrical heater, 12 – floater, 13 – accumulator, 14 – fan-coil unit, 15 – pump 2, 16 – flow meter 2, 17 – frequency converter, 18 – purge valve, 19 – valve, 20 – differential pressure control, 21 – high and low side manometers, 22 – control panel, 23 – water manometer*

Application of the Taguchi method

Traditional experimental design methods are complex and difficult to use. When the test parameters increase, it is necessary to make a great number of tests [23, 28, 35-38]. By using orthogonal arrays, the TM experimental design technique is useful in decreasing the number of experiments and also in minimizing the effects of uncontrolled factors. In an experimental study with TM, costs are reduced and significant factors can be specified in a short time [23, 28, 35-38]. The TM is not only an experimental design technique, but also a beneficial technique for high quality system design. Since it is a strong instrument for parameter design, TM was used in this study for the purpose of determining optimum temperatures in the MHP used in waste heat recovery.

In this study, the errors between measurements and predicted value were used as the loss function. The TM uses a loss function to determine the quality characteristics. The loss function is defined in terms of the deviation of a design parameter from an ideal or target value. The quality losses between initial and optimal combinations for operating temperatures error will be calculated in the section *Evaluation of operation temperatures via TM.* This loss function values are converted to a signal-to-noise, *S/N,* ratio. The *S/N* ratio [dB] characteristics can be classified into three categories, as given in eqs. (1)-(3) [37, 38]:

– nominal is the best

$$\frac{S}{N} = 10\log\left(\frac{\bar{y}}{S_y^2}\right) \tag{1}$$

– larger is better

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{2}$$

– smaller is better

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{3}$$

where $\bar{y}$ is the mean of observed data, S_y^2 - the variance of y, n - the number of observations, and y - the observed data [39].

Since the T_1, T_2, and T_c temperatures in the MHP used for the application of waste heat recovery must be at nominal values, the optimum values of the control factors were calculated with respect to the *Nominal is the best* characteristic, eq. (1) and were obtained by using the *S/N* ratio. Similarly, since ΔT_{ew}, ΔT_{cw} and T_e temperatures must be at the higher values, the optimum conditions were calculated with respect to the *Larger is better* characteristic, eq. (2) and were obtained by using the *S/N* ratio. Determination of the quality characteristics of the measured control factors was provided by *S/N* ratios.

The first step of the TM is to select an approvative orthogonal array. Taguchi aimed to obtain characteristically distinguished data by using orthogonal arrays and from these data to analyze the performance measurements for deciding optimum process parameters [37, 38]. In this study, compressor speed, n_c, wastewater temperature, T_w, and wastewater flow rate, $\dot{m}_w$, were selected as control factors and their levels were determined as shown in tab. 1. Each of control factor having three levels. Levels of the control factors were coded as "1", "2" and "3". A group of preliminary tests were performed to determine the optimal lower and higher level of control factors. Based on the outcomes from the pilot experiments, the lower and higher control parameters have been determined to investigate their influences on the operating temperatures of the MHP. Hence, the control factors used in the experiments were assigned to each column and twenty seven combinations of control factors were performed to measure responses at all combination of the factor levels. When compared with a full factorial design technique (3 × 3 × 3 = 27 trials) the number of experiments is not decreased since used

Table 1. Control factors and their levels

Factors	Symbols	Coded levels		
		1	2	3
Compressor speed, n_c, [Hz]	A	22.5	33.5	50
Wastewater temperature, T_w, [°C]	B	23.3	34.8	52
Wastewater flow rate, $\dot{m}_w$, [Lth^{-1}]	C	60	90	135

L27 orthogonal array. However, TM is a powerful tool for the design of high quality systems and it provides simple, efficient and systematic approach to optimize designs for performance, quality and cost. The TM to design of experiments is easy to adopt and apply for users with limited knowledge of statistics. Therefore, recently it has been widely employed in several industrial fields, and research works.

In this study, during Taguchi applications, a linear model analysis including the main effects of the control factor analysis was performed. Linear model analysis provides the coefficients for each factor at the low level, their *p*-values and an analysis of variance table. The linear model coefficients are straightforward to estimate, and they provide reliable estimates of the operating temperatures.

Analysis and discussion of experimental results

Operating temperatures T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c, measured in the experiments on the MHP which was used for the recovery of waste heat, were analyzed using Minitab 16.0 software.

Evaluation of operating temperatures via Taguchi method

Analysis of the S/N ratio

The twenty seven experiment combinations which were made depending on the chosen orthogonal array, experimental temperature measurement results, T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c operating temperatures estimated by TM according to the quality characteristics in eqs. (1) and (2) and the *S/N* ratios of measurement results are all given in tab. 2. Each test was repeated three times and the temperature values given in tab. 2 are the arithmetic means of the temperature measurements [$T_{1\_mean} = (T_1 + T_2 + T_3)/3$]. The TM uses *S/N* ratios to measure the variation of the experimental design. In the recovery of waste heat by the MHP, T_1, T_2, and T_c temperatures must be at nominal values. As a result from the twenty seven experimental trials, the overall mean values of these temperatures and the *S/N* ratios were calculated as 15.75 °C, 27.6 dB; 62.78 °C, 34.1 dB; and 48.97 °C, 10.1 dB, respectively. Since ΔT_{ew}, ΔT_{cw}, and T_e temperatures must be at higher values, overall mean values of these temperatures and the *S/N* ratios were calculated as: 19.40 °C, 28.8 dB; 6.0 °C, 15.5 dB; and 20.10 °C, 26.1 dB.

The effects of the level of each control factor on the quality characteristics can be analyzed using *S/N* ratios. These effects are defined and evaluated according to total mean values of experimental trial results or *S/N* ratios [39]. The optimum operating temperatures values can be calculated by means of total mean values of experimental trial results. The mean *S/N* ratios for each level of control factor and level differences of factors are given in tab. 3. The *S/N* ratio analysis gave important information on the nature of operating temperatures for the recovery of waste heat with the MHP under the chosen conditions. Higher or lower differences between the highest and the lowest *S/N* ratio values of the control factors calculated at different levels of each other were used to determine the effective factors on the operating temperatures T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c.

Table 2. Experimental results and their *S/N* ratios for operating temperatures

Trial No.	Control factors			T_1 [°C]			T_2 [°C]			ΔT_{ew} [°C]			ΔT_{cw} [°C]			T_e [°C]			T_c [°C]		
	A n_c, [Hz]	B T_w, [°C]	C $\dot{m}_w$, [Lt/h]	T_{1_mean}	T_{1_pre}	S/N [dB]	T_{2_mean}	T_{2_pre}	S/N, [dB]	ΔT_{ew_mean}	ΔT_{ew_pre}	S/N, [dB]	ΔT_{cw_mean}	ΔT_{cw_pre}	S/N, [dB]	T_{e_mean}	T_{e_pre}	S/N, [dB]	T_{c_mean}	T_{c_pre}	S/N, [dB]
1	22.5	23.3	60	13.75	12.75	21.2	49.45	47.44	28.3	8.35	7.25	18.4	1.90	1.73	5.5	14.95	13.34	23.5	41.75	40.46	36.3
2	22.5	23.3	90	13.25	14.19	26.4	50.20	50.26	28.1	4.20	4.81	12.5	1.95	1.99	5.7	13.85	13.82	22.8	41.35	41.01	45.8
3	22.5	23.3	135	13.15	16.13	20.8	47.50	48.69	28.2	5.40	3.41	14.6	1.85	2.00	5.3	14.05	14.32	23	41.25	40.94	41.3
4	22.5	34.8	60	21.35	17.61	25.0	51.55	50.97	30.0	10.65	9.74	20.5	2.15	2.21	6.6	16.60	16.24	24.4	43.25	42.89	41.8
5	22.5	34.8	90	16.00	19.05	27.1	56.20	53.79	36.4	7.05	7.30	17.0	2.80	2.47	8.9	17.05	16.72	24.6	44.45	43.45	36.9
6	22.5	34.8	135	20.75	20.99	35.4	49.30	52.22	30.8	5.85	5.90	15.3	2.45	2.49	7.7	16.25	17.21	24.2	42.05	43.37	55.5
7	22.5	52	60	30.20	29.07	46.6	57.10	58.37	38.1	13.40	13.35	22.4	2.75	2.78	8.7	19.90	19.90	26	45.05	45.35	56.1
8	22.5	52	90	31.85	30.51	26.6	64.45	61.18	45.2	8.85	10.91	18.9	3.25	3.03	10.2	20.05	20.38	26	45.55	45.90	56.2
9	22.5	52	135	32.45	32.44	31.0	56.80	59.62	29.2	8.45	9.52	18.5	2.65	3.05	8.5	20.10	20.87	26.1	44.50	45.83	36.0
10	33.5	23.3	60	7.65	6.10	40.7	60.20	57.39	24.6	6.95	8.94	16.8	3.15	3.29	9.9	7.50	8.67	17.4	45.75	46.34	42.2
11	33.5	23.3	90	7.60	7.54	22.6	56.90	60.21	35.2	8.45	6.50	18.5	2.95	3.55	9.4	8.50	9.15	18.5	45.85	46.90	39.3
12	33.5	23.3	135	9.30	9.47	36.4	61.40	58.64	27.6	4.05	5.10	11.9	4.20	3.56	12.3	9.50	9.64	19.5	47.25	46.82	42.5
13	33.5	34.8	60	11.05	10.96	29.9	62.10	60.92	38.9	10.85	11.43	20.7	3.80	3.78	11.5	11.75	11.57	21.4	49.05	48.77	56.8
14	33.5	34.8	90	13.60	12.40	25.7	58.50	63.74	38.4	9.75	8.99	19.7	3.80	4.03	11.3	11.50	12.04	21.2	48.10	49.33	50.6
15	33.5	34.8	135	13.80	14.33	30.2	66.75	62.17	30.3	7.10	7.59	17.0	4.45	4.05	12.9	13.75	12.54	22.8	50.75	49.26	43.1
16	33.5	52	60	18.70	22.41	28.4	70.65	68.32	46.0	15.75	15.04	23.9	4.55	4.34	13.2	16.25	15.23	24.2	52.25	51.23	43.4
17	33.5	52	90	22.10	23.85	34.3	64.80	71.13	29.7	13.10	12.60	22.3	4.25	4.59	12.5	15.00	15.71	23.5	50.75	51.79	43.1
18	33.5	52	135	29.05	25.79	35.4	70.80	69.57	29.4	11.40	11.21	21.1	4.65	4.61	13.3	17.00	16.20	24.6	52.40	51.71	39.3
19	50	23.3	60	3.80	2.42	11.7	63.95	64.99	45.1	11.80	12.69	21.4	4.80	4.40	13.6	4.15	4.17	12.3	51.50	51.75	37.2
20	50	23.3	90	5.00	3.86	14.1	68.70	67.81	32.1	9.35	10.25	19.4	4.80	4.65	13.6	5.15	4.64	14.2	52.55	52.30	57.4
21	50	23.3	135	4.75	5.79	15.7	63.40	66.24	36.1	9.25	8.85	19.3	4.25	4.67	12.6	5.25	5.14	14.1	51.50	52.23	37.2
22	50	34.8	60	5.70	7.28	32.1	65.20	68.52	43.7	15.25	15.18	23.7	4.45	4.88	13	6.05	7.06	15.6	53.25	54.18	43.6
23	50	34.8	90	9.30	8.72	18.3	76.10	71.34	31.1	12.95	12.74	22.2	5.35	5.14	14.6	8.25	7.54	18.2	55.50	54.74	37.9
24	50	34.8	135	10.45	10.65	29.4	67.75	69.77	38.8	10.75	11.34	20.6	4.95	5.15	13.9	7.75	8.03	17.8	54.25	54.66	43.7
25	50	52	60	15.15	18.74	29.7	72.65	75.92	33.8	19.40	18.79	25.8	5.30	5.44	14.5	9.75	10.72	19.7	55.75	56.64	44.0
26	50	52	90	21.60	20.18	26.8	82.35	78.73	33.4	16.75	16.35	24.5	6.00	5.70	15.5	11.85	11.20	21.5	58.50	57.19	38.4
27	50	52	135	24.00	22.11	23.0	80.40	77.17	32.8	15.65	14.96	23.9	5.85	5.71	15.3	12.00	11.69	21.5	58.00	57.12	38.3
Minimum				3.80	2.42	11.7	47.50	47.44	24.6	4.05	3.41	11.9	1.85	1.73	5.3	4.15	4.17	12.3	41.25	40.46	36.0
Maximum				32.45	32.44	46.6	82.35	78.73	46.0	19.40	18.79	25.8	6.00	5.71	15.5	20.10	20.87	26.1	58.50	57.19	57.4
Overall of mean				15.75	15.75	27.6	62.78	62.78	34.1	10.40	10.40	19.7	3.83	3.83	11.1	12.36	12.36	21.1	48.97	48.97	43.9

Table 3. Mean *S/N* [dB] ratios of control factors

Level	Compressor suction gas temperature, [dB]			Compressor discharge gas temperature, [dB]			Temperature difference of water entering and leaving from evaporator, [dB]		
	A	B	C	A	B	C	A	B	C
	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$
1	28.88	23.27	29.48	32.71	31.72	36.51	17.58	16.99	21.51
2	31.51	28.12	24.65	33.34	35.38	34.40	19.12	19.63	19.44
3	22.31	31.31	28.58	36.34	35.29	31.47	22.31	22.37	18.04
Δ*	9.20	8.05	4.83	3.63	3.66	5.04	4.73	5.38	3.48
Rank	1	2	3	3	2	1	2	1	3
Level	Temperature difference of water entering and leaving from condenser, [dB]			Evaporation temperature, [dB]			Condensation temperature, [dB]		
	A	B	C	A	B	C	A	B	C
	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$
1	7.46	9.75	10.71	24.51	18.37	20.50	12.38	8.85	10.90
2	11.79	11.15	11.29	21.45	21.14	21.17	10.69	11.79	11.29
3	14.04	12.41	11.30	17.21	23.66	21.50	7.24	9.68	8.12
Δ*	6.59	2.66	0.59	7.30	5.29	1.00	5.14	2.68	3.16
Rank	1	2	3	1	2	3	1	3	2

* Δ = difference between maximum and minimum.

From tab. 4, it is possible to identify the sequence of influence of the control factors on each operating. While the most effective control factor on the compression suction gas temperature, T_1, and the temperature difference of water entering and leaving the evaporator, ΔT_{ew}, was wastewater temperature, T_w, the most effective control factor on the compressor discharge gas temperature, T_2, the temperature difference of water entering and leaving the condenser, ΔT_{cw}, evaporation temperature, T_e, and condensation temperature, T_c, happened to be the compressor speed, n_c. Distribution of the means of *S/N* ratios and optimum level of control factors for operating temperatures are shown in fig. 3. From this figure, the effects of each factor at different level can be observed. From tab. 4 and fig. 3 the optimum level of the control factors for T_1 was determined to be: ($n_{c2} - T_{w2} - \dot{m}_{w2}$) $n_c = 33.5$ Hz, $T_w = 34.8$ °C, $\dot{m}_w = 90$ Lt/h; for T_2 ($n_{c2} - T_{w2} - \dot{m}_{w3}$) $n_c = 33.5$ Hz, $T_w = 34.8$ °C, $\dot{m}_w = 135$ Lt/h; for ΔT_{ew} ($n_{c3} - T_{w3} - \dot{m}_{w1}$) $n_c = 50$ Hz, $T_w = 52$ °C, $\dot{m}_w = 60$ Lt/h; for ΔT_{cw} ($n_{c3} - T_{w3} - \dot{m}_{w3}$) $n_c = 50$ Hz, $T_w = 52$ °C, $\dot{m}_w = 135$ Lt/h; for T_e ($n_{c1} - T_{w3} - \dot{m}_{w3}$) $n_c = 22.5$ Hz, $T_w = 52$ °C, $\dot{m}_w = 135$ Lt/h; and for T_c ($n_{c2} - T_{w2} - \dot{m}_{w3}$) $n_c = 33.5$ Hz, $T_w = 34.8$ °C, $\dot{m}_w = 135$ Lt/h. Variations of the operating temperatures depending on the variation of control factor levels are shown in fig. 3 and the control factors have similar effects on T_1 and T_e, figs. 3(a) and 3(e). With the increase of n_c, the flow rate of the refrigerant circulating in the system and compression ratio with increasing amount of refrigerant swept were increased. The evaporator heat load remained the same due to constant waste water temperature and flow rate through the evaporator. This caused a decrease in T_1 and T_e and an increase in T_2, T_c, ΔT_{ew} and ΔT_{cw}. In addition, T_w affected all of the temperature values of the system by causing them to increase.

Table 4. Response table for means for operating temperatures

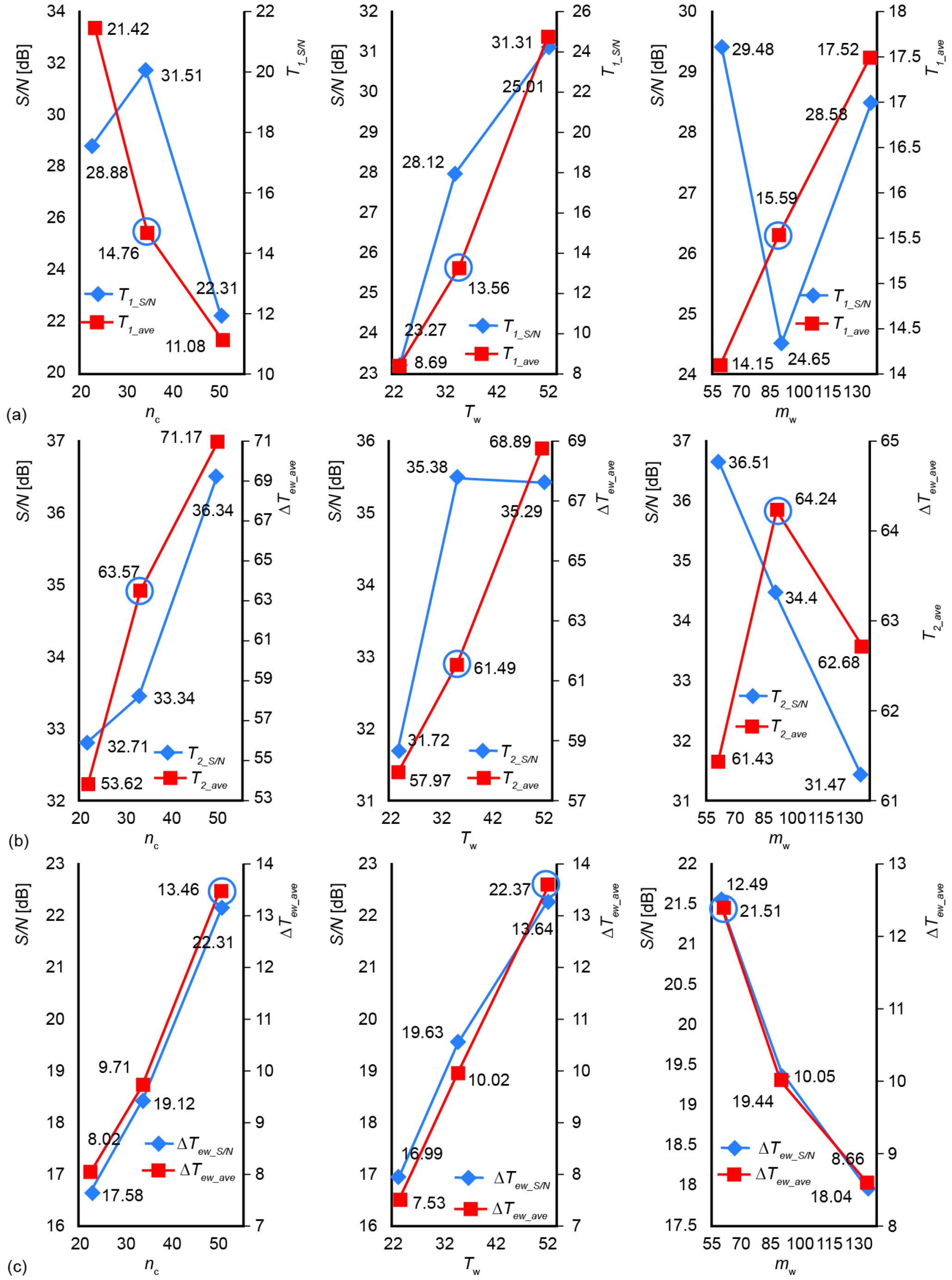
Level	Compressor suction gas temperature, T_1 [°C]			Compressor discharge gas temperature, T_2, [°C]			Temperature difference of water entering and leaving from evaporator, ΔT_{ew}, [°C]		
	A	B	C	A	B	C	A	B	C
	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$
1	21.42	8.69	14.15	53.62	57.97	61.43	8.02	7.53	**12.49**
2	**14.76**	**13.56**	**15.59**	**63.57**	**61.49**	64.24	9.71	10.02	10.05
3	11.08	25.01	17.52	71.17	68.89	**62.68**	**13.46**	**13.64**	8.66
Δ*	10.33	16.32	3.37	17.55	10.92	2.82	5.44	6.11	3.83
Rank	2	1	3	1	2	3	2	1	3
Level	Temperature difference of water entering and leaving from condenser, ΔT_{cw}, [°C]			Evaporation temperature, T_e [°C]			Condensation temperature, T_c, [°C]		
	A	B	C	A	B	C	A	B	C
	n_c	T_w	$\dot{m}_w$	n_c	$\dot{m}_w$	$\dot{m}_w$	n_c	T_w	$\dot{m}_w$
1	2.42	3.32	3.65	**16.98**	9.21	11.88	43.24	46.53	48.62
2	3.98	3.80	3.91	12.31	12.11	12.36	**49.13**	**48.96**	49.18
3	**5.08**	**4.36**	**3.92**	7.80	**15.77**	**12.85**	54.53	51.42	**49.11**
Δ*	2.67	1.04	0.27	9.18	6.56	0.97	11.29	4.89	0.56
Rank	1	2	3	1	2	3	1	2	3

* Δ = difference between maximum and minimum.

With the increasing of T_w, the evaporator heat load also increased because of higher waste water temperature and this caused an increase in the temperature values of T_1, T_e, T_2, T_c, ΔT_{ew}, and ΔT_{cw}. With the increasing of n_c and T_w, T_2, and T_c increased as well. With the increase of T_w, the increase of the evaporator heat load gave rise to an increase in the condenser heat load and consequently, the T_c also increased. ΔT_{ew} decreased significantly and T_1 also increased with the increasing of $\dot{m}_w$. The increase of $\dot{m}_w$ did not notably affect the T_e; the temperature variation of T_e was approximately 1 °C, and therefore, the T_c value was not affected significantly. Depending on the variation of the T_c of the system, the T_2 and ΔT_{cw} values were not affected much either.

Analysis of variance

In this study, ANOVA was also used to analyze the effects of control factors on operating temperatures. The experimental results were evaluated at a confidence level of 95%. The ANOVA values belonging to experimental results for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c are given in tab. 5. The significance of control factors in ANOVA is determined by comparing F value of each control factor and $F_{0.05}$ value from the table. Contribution percentage [%] is also used to determine the significance of the control factors. In consequence of the conducted assessments, the factors that contribution percentages less than 5% and error values for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c were removed from tab. 5. The residual error term and total error variance which includes this error were combined by the pooling method. These terms removed from the table were marked with sign bold font. The contribution percentages of the control factors are given for each operating temperature, tab. 5(a)-(f).



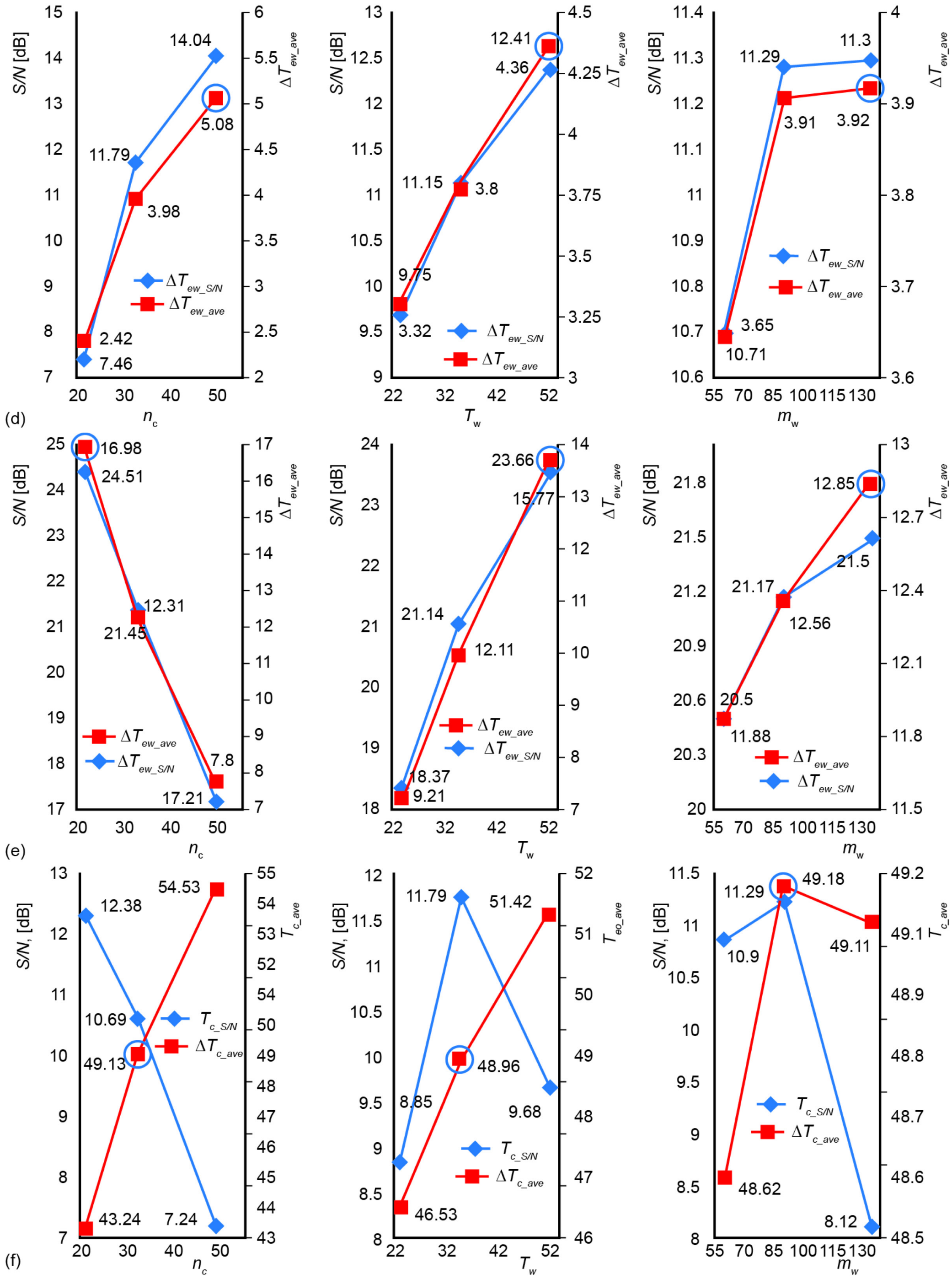


Figure 3. Distribution of the means of *S*/*N* ratios and optimum level of control factors for operating temperatures; (a) T_1, (b) T_2, (c) ΔT_{ew}, (d) ΔT_{cw}, (e) T_e, (f) T_c

Table 5(a)-(f). The ANOVA results for operating temperatures

(a) Compressor suction gas temperature, T_1

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	493.80	246.90	52.26	25.95
T_w	2	1263.28	631.64	133.71	66.38
$\dot{m}_w$	2	**51.54**	25.77	–	–
Residual error	20	94.48	4.72	–	–
Pooled error	(21)	(146.02)	6.95	–	7.67
Total	26	1903.10			100.00

(b) Compressor discharge gas temperature, T_2

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	1394.30	697.15	56.77	62.39
T_w	2	559.25	279.63	22.77	25.02
$\dot{m}_w$	2	**35.85**	17.93	–	–
Residual error	20	245.61	12.28	–	–
Pooled error	(21)	(281.46)	13.40	–	12.59
Total	26	2235.02			100.00

(c) Temperature difference of water entering and leaving from evaporator, ΔT_{ew}

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	139.49	69.75	54.07	34.64
T_w	2	169.66	84.83	65.76	42.13
$\dot{m}_w$	2	67.76	33.88	26.27	16.82
Residual error	20	25.80	1.29	–	6.41
Pooled error	–	–	–	–	–
Total	26	402.71			100.00

(d) Temperature difference of water entering and leaving from condenser, ΔT_{cw}

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	32.31	16.16	140.57	80.87
T_w	2	4.92	2.46	21.40	12.31
$\dot{m}_w$	2	**0.42**	0.21	–	–
Residual error	20	2.30	0.11	–	–
Pooled error	(21)	(2.72)	0.13	–	6.81
Total	26	39.95			100.00

(e) Evaporation temperature, T_e

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	379.08	189.54	277.65	64.11
T_w	2	194.27	97.14	142.29	32.86
$\dot{m}_w$	2	**4.25**	2.13	–	–
Residual error	20	13.65	0.68	–	–
Pooled error	(21)	(17.9)	0.85	–	3.03
Total	26	591.26			100.00

(f) Condensation temperature, T_c

Source	Degree of freedom	Sum of squares	Variance	F-ratio	Contribu-tion [%]
n_c	2	573.82	286.91	282.33	81.58
T_w	2	107.56	53.78	52.92	15.29
$\dot{m}_w$	2	**1.64**	0.82	–	–
Residual error	20	20.32	1.02	–	–
Pooled error	(21)	(21.96)	1.05	–	3.13
Total	26	703.34			100.00

– The most effective factors on T_1 were T_w (66.38%) and n_c (25.95%).
– The most effective factors on ΔT_{ew} were T_w (42.13%), n_c (34.64%), and $\dot{m}_w$ (16.82%).
– The most effective factors on T_2 were n_c (62.39%) and T_w (25.02%).
– The most effective factors on ΔT_{cw} were n_c (80.39%) and T_w (12.31%).
– The most effective factors on T_e were n_c (64.11%) and T_w (32.86%).
– The most effective factors on T_c were n_c (81.58%) and T_w (15.29%).

According to results obtained from tab. 5, it is observed that T_1 and ΔT_{ew} most affected from T_w. Because of increasing temperature of the wastewater passed through the evaporator, heat transfer between the refrigerant and the wastewater increased and so T_1 and ΔT_{ew} increased. While it is observed that effects of n_c on the T_1 and ΔT_{ew} are less than T_w (25.95% and 34.64%, respectively). Its effects on the T_2, T_c, ΔT_{cw}, and T_e are more than the effects of T_w (62.39%, 80.39%, 64.11%, and 81.58%, respectively). The $\dot{m}_w$ only affects ΔT_{ew} (16.82%), its effects on the other temperatures were not observed.

Determination of optimal operating temperatures

The models determining optimal operating temperatures are defined with the total effects generated by the control factors. The factors are equals to the sum of each individual effect. The optimum levels are evaluated by considering the pooled error losses [39]. The optimal operating temperatures were obtained by taking into account the influential factors within the evaluated optimum combination. Optimal operating temperatures in terms of the aforementioned control factors can be easily determined from fig. 3, ant tab. 4. The optimum control factors are A_2B_2 ($n_{c2} - T_{w2}$), $A_2B_2C_3$ ($n_{c2} - T_{w2} - \dot{m}_{w3}$), A_3B_3 ($n_{c3} - T_{w3}$), A_3B_3 ($n_{c3} - T_{w3}$), A_1B_3 ($n_{c1} - \mathrm{T}_{w3}$), and A_2B_2 ($n_{c2} - T_{w2}$) for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c, respectively. Therefore, the predicted optimum values of T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c operating temperatures were calculated respectively by the aid of eqs. (4)-(9).

$$\mu_{\mathrm{opt}\_T_1} = \overline{T}_{T_1} + (A_2 - \overline{T}_{T_1}) + (B_2 - \overline{T}_{T_1}) \tag{4}$$

$$\mu_{\mathrm{opt}\_T_2} = \overline{T}_{T_2} + (A_2 - \overline{T}_{T_2}) + (B_2 - \overline{T}_{T_2}) \tag{5}$$

$$\mu_{\mathrm{opt}\_\Delta T_{ew}} = \overline{T}_{\Delta \mathrm{T}_{ew}} + (A_3 - \overline{T}_{\Delta \mathrm{T}_{ew}}) + (B_3 - \overline{T}_{\Delta \mathrm{T}_{ew}}) + (C_1 - \overline{T}_{\Delta \mathrm{T}_{ew}}) \tag{6}$$

$$\mu_{\mathrm{opt}\_\Delta T_{cw}} = \overline{T}_{\Delta T_{cw}} + (A_3 - \overline{T}_{\Delta T_{cw}}) + (B_3 - \overline{T}_{\Delta T_{cw}}) \tag{7}$$

$$\mu_{\mathrm{opt}\_T_e} = \overline{T}_{T_e} + (A_1 - \overline{T}_{T_e}) + (B_3 - \overline{T}_{T_e}) \tag{8}$$

$$\mu_{\mathrm{opt}\_T_c} = \overline{T}_{T_c} + (A_2 - \overline{T}_{T_c}) + (B_2 - \overline{T}_{T_c}) \tag{9}$$

Table 4 shows the following values: for T_1, A_2 = 14.76 °C and B_2 = 13.56 °C; for T_2, A_2 = 63.57 °C and B_2 = 61.49 °C; for ΔT_{ew}, A_3 = 13.46 °C, B_3 = 13.639 °C, and C_1 = 12.49 °C; for ΔT_{cw}, A_3 = 5.08 °C and B_3 = 4.36 °C; for T_e, A_1 = 16.98 °C and B_3 = 15.77 °C, and for T_c, A_2 = 49.13 °C and B_2 = 48.96 °C. From tab. 3, $\overline{T}_{T_1}$ = 15.75 °C, $\overline{T}_{T_2}$ = 62.78 °C, $\overline{T}_{\Delta \mathrm{T}_{ew}}$ = 10.40 °C, $\overline{T}_{\Delta T_{cw}}$ = 3.83 °C, $\overline{T}_{T_c}$ = 12.36 °C and $\overline{T}_{T_c}$ = 48.97 °C values were taken. These values were put into eqs. (4)-(9) and the following optimal operating temperatures were calculated: $\mu_{\mathrm{opt}\_T_1}$ = = 12.57 °C, $\mu_{\mathrm{opt}\_T_2}$ = 62.28 °C, $\mu_{\mathrm{opt}\_\Delta T_{ew}}$ = 18.79 °C, $\mu_{\mathrm{opt}\_\Delta T_{cw}}$ = 5.61 °C, $\mu_{\mathrm{opt}\_T_e}$ = 20.39 °C, and $\mu_{\mathrm{opt}\_T_c}$ = 49.14 °C.

Confidence intervals of estimated means

Confidence interval (*CI*) is the maximum and minimum value between which the true average should fall at some stated percentage of confidence [38]. The *CI* was employed to verify the quality characteristics of the confirmation experiments. At the level of 95%, the *CI* for the predicted optimal values was calculated by the aid of the equation:

$$CI = \sqrt{F_{\alpha:1,V_2} V_{\text{error}} \left(\frac{1}{n_{\text{eff}}} + \frac{1}{R} \right)} \tag{10}$$

where $F_{\alpha:1,V2}$ is the F-ratio of significant level α, α – the significant level, 1-α – the confidence level, V_2 – the degree of freedom of pooled error variance, V_{error} – the pooled error variance, R – the number of repeated trials, n_{eff} – the number of effective measured results. The $F_{\alpha:1,V2}$ value is 3.46 for T_1, T_2, ΔT_{cw}, T_{e} and T_{c}. The $F_{\alpha:1,V2}$ value is 3.49 for ΔT_{ew}. Residual error variance values (V_{error}) for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_{e}, and T_{c} were taken from tab. 5 as 6.95, 13.40, 1.29, 0.13, 0.85 and 1.05, respectively; n_{eff} was calculated through eq. (11):

$$n_{\text{eff}} = \frac{N}{1 + T_{\text{dof}}} \tag{11}$$

where N is the total number of tests (27), and T_{dof} – the sum of the degrees of freedom (T_{dof} is 4 for T_1, T_2, ΔT_{cw}, T_{e}, and T_{c} and T_{dof} is 6 for ΔT_{ew}) of the significant parameters. When all of the calculated values were put into eq. (10), the values $CI_{T_1} = \pm 3.53$, $CI_{T_2} = \pm 4.90$, $CI_{\Delta T_{\text{ew}}} = \pm 1.63$, $CI_{\Delta T\text{cw}} = \pm 0.48$, $CI_{T\text{e}} = \pm 1.23$, and $CI_{T\text{c}} = \pm 1.37$ were obtained. At a confidence level 95%, the confidence intervals for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_{e}, and T_{c} were calculated 8.87 < 12.57 < 15.93 °C, 57.27 < 62.28 < 67.08 °C, 17.16 < 18.79 < 20.43 °C, 5.23 < 5.61 < < 6.20 °C, 19.64 < 20.39 < 22.11 °C, and 47.88 < 49.14 < 50.63 °C, respectively.

Confirmation experiments

Three confirmation tests conducted with regard to the optimal levels of control factors. Means of measurements are given in tab. 6. These means falls within the determined confidence interval (8.87 < 13.9 < 15.93 °C, 57.27 < 66.1 < 67.08 °C, 17.16 < 18.55 < 20.43 °C, 5.23 < 5.65 < 6.20 °C, 19.64 < 20.45 < 22.11 °C, 47.88 < 48.9 < 50.63 °C). Therefore, the system optimization for operating temperatures was successfully carried out by using the TM at a significance level of 0.05.

The comparisons of the operating temperatures to optimal tests and the predicted combinations $A_2B_2C_2$, $A_2B_2C_3$, $A_3B_3C_1$, $A_3B_3C_3$, $A_1B_3C_3$, and $A_2B_2C_3$ and the combination $A_2B_1C_1$ ($n_{\text{c}} = 33.5$ Hz, $T_{\text{w}} = 23.3$ °C, $\dot{m}_{\text{w}} = 60$ Lt/h) selected from twenty seven initial trials are given in tab. 6. In these comparisons, T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_{e}, and T_{c} values were eliminated from 7.65, 60.20, 6.95, 3.15, 7.50, and 45.75 to 13.35, 66.10, 18.55, 5.65, 20.45, 48.90, respectively. The improved accuracy efficiency because of the optimal combinations was increased up to 75.51%, 9.80%, 166.91%, 79.37%, 172.67%, and 6.89% for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_{e}, and T_{c}, respectively. The *S/N* ratios are also given in tab. 6 to compare the quality characteristics of the initial and optimal conditions.

Table 6. Experimental conditions for confirmation tests and comparative results

	Compressor suction gas temperature, T_1 [°C]			Compressor discharge gas temperature, T_2 [°C]			Temperature difference of water entering and leaving from evaporator, ΔT_{ew} [°C]		
	Level	*T*	*S/N*	Level	*T*	*S/N*	Level	*T*	*S/N*
Initial combination	$A_2B_1C_1$	7.65	40.7	$A_2B_1C_1$	60.20	24.6	$A_2B_1C_1$	6.95	16.8
Optimal combination (exp.)	$A_2B_2C_2$	13.35	24.7	$A_2B_2C_3$	66.10	28.3	$A_3B_3C_1$	18.55	25.4
Optimal combination (pre.)	$A_2B_2C_2$	12.40	25.7	$A_2B_2C_3$	62.17	30.3	$A_3B_3C_1$	18.79	25.8
Quality loss [%]	2.48			42.54			13.71		
	Temperature difference of water entering and leaving from condenser, ΔT_{cw} [°C]			Evaporation temperature, T_e [°C]			Condensation temperature, T_c [°C]		
	Level	*T*	*S/N*	Level	*T*	*S/N*	Level	*T*	*S/N*
Initial combination	$A_2B_1C_1$	3.15	9.9	$A_2B_1C_1$	7.50	17.4	$A_2B_1C_1$	45.75	42.2
Optimal combination (exp.)	$A_3B_3C_3$	5.65	14.9	$A_1B_3C_3$	20.45	26.2	$A_2B_2C_3$	48.90	35.2
Optimal combination (pre.)	$A_3B_3C_3$	5.71	15.3	$A_1B_3C_3$	20.87	26.1	$A_2B_2C_3$	49.26	43.1
Quality loss [%]	31.51			13.09			19.87		

Quality losses

The quality losses between initial and optimal combinations for operating temperatures error are calculated [39]:

$$\frac{L_{\text{opt}}(y)}{L_{\text{ini}}(y)} \approx \left(\frac{1}{2}\right)^{\Delta\eta/3} \tag{12}$$

where, $L_{\text{opt}}(y)$ and $L_{\text{ini}}(y)$ are optimal and initial combinations, respectively, and $\Delta\eta$ – the difference between *S*/*N* ratios of optimal and initial combinations. The differences of *S*/*N* ratios that can be used to evaluate the quality loss eq. (12) of the optimal combination for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c, respectively were found as 16.0, 3.7, 8.6, 5.0, 8.8, and 7.0, respectively. Using eq. (12), the quality loss of T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c were calculated as 0.0248, 0.4254, 0.1371, 0.3151, 0.1309, and 0.1987. Thereby, the quality loss of T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c at the optimal combinations became only 2.48%, 42.54%, 13.71%, 31.51%, 13.09%, and 19.87% of the initial combination, respectively (tab. 6). When these results were evaluated, the quality losses for the T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c were reduced to 97.52%, 57.46%, 86.29%, 68.49%, 86.91%, and 80.13% by using the TM, respectively.

Conclusions

In this work, the effect of control parameters such as compressor speed, n_c, wastewater temperature, T_w, and mass flow rate, $\dot{m}_w$, on the operating temperatures of the MHP are studied. The experimental studies are performed based on Taguchi's *L*27 full factorial design of experiment and determined the optimal control parameters for the MHP. The following conclusions can be drawn from the experimental study.

- Nominal levels of the control factors for the T_1, T_2, and T_c temperatures in the MHP used in the waste heat recovery application were specified as T_1, n_c = 33.5Hz, T_w = 34.8 °C, $\dot{m}_w$ = 90 Lt/h; for T_2, n_c = 33.5 Hz, T_w = 34.8 °C, $\dot{m}_w$ = 135 Lt/h; and for T_c, n_c = 33.5 Hz, T_w = 34.8 °C, $\dot{m}_w$ = 135 Lt/h.
- The optimal temperatures were obtained for for ΔT_{ew}, n_c = 50 Hz, T_w = 52 °C, $\dot{m}_w$ = 60 Lt/h; for ΔT_{cw}, n_c = 50 Hz, T_w = 52 °C, $\dot{m}_w$ = 135 Lt/h; and for T_e, n_c = 22.5 Hz, T_w = 52 °C, $\dot{m}_w$ = 135 Lt/h.
- The most effective factors on the compressor suction gas temperature and discharge gas temperature were wastewater temperature 66.38%, 62.39% and compressor speed 25.95%, 25.02%, respectively.
- The significant influential parameters on the temperature difference of water entering and leaving from evaporator were obtained the wastewater temperature with percentage contribution of 42.13% and the compressor speed has a meaningful correlation with a percentage contribution of 80.39% on the temperature difference of water entering and leaving from condenser.
- The effects of compressor speed on evaporation and condensation temperature were measured by factors of 64.11% and 81.58%, respectively.
- The operating temperatures were predicted with the TM and determined the optimal operating temperatures for T_1, T_2, ΔT_{ew}, ΔT_{cw}, T_e, and T_c.
- The findings of this experimental study and optimization models are expected to be useful guidelines for the mechanical heat pump tested, it could be varied in other cases.

Acknowledgment

This work was supported by the Uludag University Commission of Scientific Research Projects, project number: M-2008/63.

Nomenclature

a – significant level
CI – confidence interval
$\cos\varphi$ – power factor
$F_{a,1,fe}$ – F ratio of significant level a
L_{ini} – initial combinations
L_{opt} – optimal combinations
$\dot{m}_w$ – wastewater flow rate, [Lth^{-1}]
N – total number of tests
n_c – compressor speed, [rpm]
n_{eff} – number of effective measured results
R – number of repeated trials
S/N – signal-to-noise, [dB]
S_y^2 – variance of y
T_1 – compressor suction gas temperature, [°C]
T_2 – compressor discharge gas temperature, [°C]
T_c – condensation temperature, [°C]
T_{dof} – sum of the degrees of freedom
T_e – evaporation temperature, [°C]
T_w – wastewater temperature, [°C]
V_2 – degree of freedom of pooled error variance
V_{error} – residual error variance values
y – observed data
$\bar{y}$ – mean of observed data
T – total mean of temperature, [°C]
ΔT – temperature difference, [°C]

Greek symbols

$\Delta\eta$ – difference between S/N ratios of optimal and initial combinations, [dB]
μ_{opt} – predicted optimum values of operating temperatures, [°C]

Subscripts

cw – water entering and leaving the condenser
ew – water entering and leaving the evaporator
mean – mean
pre – predicted

Acronyms

ANOVA – analysis of variance
MHP – mechanical heat pump
TM – Taguchi method
TXV – thermostatic expansion valve

References

[1] Al-Rabghi, O. M., *et al.*, Recovery and Utilization of Waste Heat, *Heat Recovery System CHP, 13* (1993), 5, pp. 463-470
[2] Lazzarin, R. M., Heat Pumps in Industry-I. Equipment, *Heat Recovery System CHP, 14* (1994), 6, pp. 581-597
[3] Lazzarin, R. M., Heat Pumps in Industry-II. Applications, *Heat Recovery System CHP, 15* (1995), 3, pp. 305-317
[4] Reay, D. A., *et al.*, *Heat Pumps Design and Applications*, Pergamon Press, Oxfort, UK, 1979
[5] Wittwer, D., Environmental Benefits of Heat Pumps, International Sustainable Energy Organization for Renewable Energy and Energy Efficiency, ISEO, Geneva, Switzerland, 2000
[6] Ozgener, O., *et al.*, Experimental Performance Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System, *Energy Buildings, 37* (2005), 1, pp. 101-110
[7] Tran, C. T., *et al.*, *In situ* Measurement Methods of Air to Air Heat Pump Performance, *International Journal of Refrigeration, 36* (2013), 5, pp. 1442-1455
[8] Cakir U., *et al.*, An Experimental Exergetic Comparison of Four Different Heat Pump Systems Working at Same Conditions: As Air to Air, air to Water, Water to Water and Water to Air, *Energy, 58* (2013), Sept., pp. 210-219
[9] Lee, J. S., *et al.*, Transient Performance Characteristics of a Hybrid Ground-Source Heat Pump in the Cooling Mode, *Apply Energy, 123* (2014), June, pp. 121-128
[10] Li, R, Ooka R., *et al.,* Theoretical Analysis on Ground Source Heat Pump and Air Source Heat Pump Systems by the Concepts of Cool and Warm Energy, *Energy Buildings, 75* (2014), June, pp. 447-455
[11] Chaturvedi, S. K., *et al.*, Solar-Assisted Heat Pump – A Sustainable System for Low-Temperature Water Heating Applications, *Energy Conversation & Management, 77* (2014), Jan., pp. 550-557
[12] Jung, H. W., *et al.*, Performance Optimization of a Cascade Multi-Functional Heat Pump in Various Operation Modes, *International Journal of Refrigeration, 42* (2014), June, pp. 57-68
[13] Baek, N. C., *et al.*, A Study on the Design and Analysis of a Heat Pump Heating System Using Wastewater as a Heat Source, *Solar Energy, 78* (2005), 3, pp. 427-440
[14] Huang, K., *et al.*, Heat Pump for School Bathroom Heat Recovery, *Proceedings,* Renewable Energy Resources and a Greener Future ICEBO2006, Shenzhen, China, 2006
[15] Ajah, A. N., *et al.*, On the Robustness, Effectiveness and Reliability of Chemical and Mechanical Heat Pumps for Low-Temperature Heat Source District Heating: A Comparative Simulation-Based Analysis and Evaluation, *Energy, 33* (2008), 6, pp. 908-929
[16] Pulat, E., *et al.*, Waste-Heat Recovery Potential in Turkish Textile Industry: Case Study for City of Bursa, *Renewable Sustainable Energy Reviews, 13* (2009), 3, pp. 663-672
[17] Salah El-Din, M. M., Optimal Utilization of Waste Heat from Heat Engines by Use of a Heat Pump, *Energy Convers Manage, 40* (1999), 2, pp. 937-949
[18] Braun, J. E., *et al.*, Energy Efficiency Analysis of Air Cycle Heat Pump Dryers, *International Journal of Refrigeration, 25* (2002), 7, pp. 954-965
[19] Soylemez, M. S., Optimum Heat Pump in Drying Systems with Waste Heat Recovery*, Journal of Food Engineering, 74* (2006), 3, pp. 292-298
[20] Pal, U. S., *et al.*, Heat Pump Drying of Green Sweet Pepper, *Drying Technology, 26* (2008), 12, pp. 1584-1590
[21] Minea, V., Drying Heat Pumps-Part I: System Integration, *International Journal of Refrigeration, 36* (2013), 3, pp. 643-658
[22] Chamoun, M., *et al.*, Experimental and Numerical Investigations of a New High Temperature Heat Pump for Industrial Heat Recovery Using Water as Refrigerant, *International Journal of Refrigeration, 44* (2014), Aug., pp. 177-188
[23] Bendell, A., *et al.*, *Taguchi Methods: Applications in World Industry*, Springer-Verlag, New York, USA, 1989
[24] Esme, U., Application of Taguchi Method for the Optimization of Resistance Spot Welding Process, *Arabian Journal for Science and Engineering, 34* (2009), 2B, pp. 519-528
[25] Roy, R. K., *A Primer on the Taguchi Method*, 2nd ed., Society of Manufacturing Engineers, Dearborn, Mich., USA, 2010
[26] Comakli, O., *et al.*, Determination of Optimum Working Conditions in Heat-Pumps Using Nonazeotropic Refrigerant Mixtures, *Energy Conversation & Management, 40* (1999), 2, pp. 193-203

[27] Comakli, K., *et al*., Determination of Optimum Working Conditions R22 and R404A Refrigerant Mixtures in Heat-Pumps Using Taguchi Method, *Applied Energy, 86* (2009), 11, pp. 2451-2458
[28] Coskun, S., *et al*., Evaluation of Control Parameters' Effects on System Performance with Taguchi Method in Waste Heat Recovery Application Using Mechanical Heat Pump, *International Journal of Refrigeration, 35* (2012), 4, pp. 795-809
[29] Sivasakthivel, T., *et al*., Optimization of Operating Parameters of Ground Source Heat Pump System for Space Heating and Cooling by Taguchi Method and Utility Concept, *Applied Energy, 116* (2014), Mar., pp. 76-85
[30] Verma, V., *et al*., Optimization of Solar Assisted Ground Source Heat Pump System for Space Heating Application by Taguchi Method and Utility Concept, *Energy & Buildings, 82* (2014), Oct., pp. 296-309
[31] Bhoite, I., *et al*., Thermal Analysis of Heat Pipe Using Taguchi Method, *UREAT International Journal of Research in Engineering and Advanced Technology, 2* (2014), 2, pp. 1-5
[32] Lu, S. M., *et al*., Optimum Design of Natural Circulation Solar-Water-Heater by the Taguchi Method, *Energy, 28* (2003), 7, pp. 741-750
[33] Pinar, A. M., *et al*., Optimization of Counter Flow Ranque-Hilsch Vortex Tube Performance Using Taguchi Method, *International Journal of Refrigeration, 32* (2009), 6, pp. 1487-1494
[34] Chen, H. C., *et al*., Application of Taguchi Method to Optimize Extracted Ginger Oil in Different Drying Conditions, *Proceedings,* IPCBEE 2011 International Conference on Food Engineering and Biotechnology, Bangkok, Thailand, 2011, Vol. 9, pp. 310-316
[35] Asilturk, I., *et al*., Determining the Effect of Cutting Parameters on Surface Roughness in Hard Turning Using the Taguchi Method, *Measurement, 44* (2011), 9, pp. 697-1704
[36] Hascalik, A., *et al*., Optimization of Turning Parameters for Surface Roughness, and Tool Life Based on the Taguchi Method, *International Journal of Advanced Manufacturing Technology, 38* (2008), Sept., pp. 896-903
[37] Koksoy, O., *et al.,* Solution to the Taguchi's Problem with Correlated Responses, *Gazi University Journal of Science, 17* (2004), 1, pp. 59-70
[38] Ross, P. J., *Taguchi Techniques for Quality Engineering*, McGraw-Hill, New York, USA, 1996
[39] Cicek, A., *et al.,* Application of Taguchi Method for Surface Roughness and Roundness Error in Drilling of AISI 316 Stainless Steel, *Strojniški Vestnik – Journal of Mechanical Engineering, 58* (2012), 3, pp. 165-174

Paper submitted: March 23, 2015
Paper revised: March 8, 2016
Paper accepted: March 9, 2016