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Determination of coefficient of performance of mechanical vapour recompression heat pump

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Abstract. Mechanical vapour recompression heat pump systems are widely used in the industry - in evaporator and distillation installations, in seawater desalination and industrial wastewater treatment plants. The estimation of the energy efficiency level of this type of system is based on values of two basic parameters: specific energy consumption for production of 1 kg clean water (condensate) and actual coefficient of performance of heat pump system. The object of study is experimental determination of value of actual coefficient of performance of mechanical vapour recompression heat pump system for wastewater treatment. A mathematical regression equation between the actual coefficient of performance μ and two significant factors – temperature of secondary water vapour t_{sv} and compression ratio of water vapour in mechanical compressor of heat pump system σ is received. The analysis show that actual coefficient of performance μ highly depends of value of compression ratio σ and less depends of values of temperature of secondary vapour t_{sv}. It conclude that MVR heat pump system, in order to operate with high values of the actual coefficient of performance should be working to high values of temperature of secondary vapour and low values of compression ratio of water vapour in mechanical compressor.

1 Introduction

In process of wastewater treatment, mechanical vapour recompression (MVR) heat pump system separates wastewater flow into two flows – clean water (condensate) and concentrate sludge with high values of organic dry matters. A condensate with high temperature can be reused in various industrial processes, where a heat or clean water is needed. MVR heat pump system increases the pressure of secondary vapour, produced by the evaporator and use compressed vapour with high pressure as a primary vapour flow. Receiving of clean hot water by this method is made by low energy cost, because when the process of evaporation is started, there is no need to supply additional energy to maintenance the process.

Energy efficiency of MVR heat pump system is based on the values of two basic parameters: specific energy consumption for production of 1 kg condensate (Wh/kg) and actual coefficient of performance (-) [1, 2]. In wastewater MVR heat pump systems the

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difference between evaporation temperature of wastewater in separator and temperature of the compressed vapour is very small, which determines a high values of coefficient of performance of MVR heat pump systems (from 10 to 30) [3, 4, 5].
In this study a relation between actual coefficient of performance and two significant factors – temperature of secondary vapour and compression ratio of water vapour in mechanical compressor of MVR heat pump system is received.

2 Pilot MVR heat pump system

For the purpose of the study a pilot MVR heat pump system for wastewater treatment is built. The installation is located in Plovdiv, Bulgaria, at laboratory of the University Of Food Technology – Plovdiv. Schematic diagram of MVR heat pump system is shown on Figure 1.

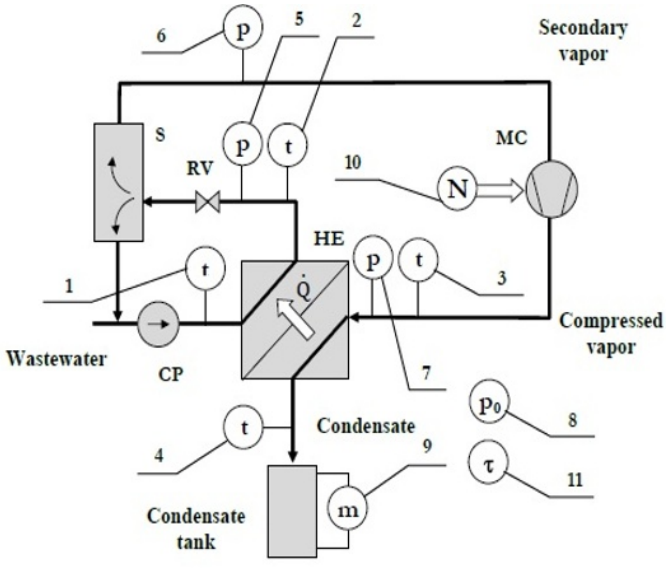

Fig. 1. Schematic diagram of mechanical vapour recompression heat pump system [6]

The wastewater goes to a plate heat exchanger HE, where it is heated by secondary vapour to a higher temperature. The temperature of wastewater at inlet of heat exchanger HE is measured with thermometer 1. Since the circulation pump CP creates a certain pressure in the heat exchanger HE, wastewater is in the state of non-boiling liquid. The temperature of wastewater at outlet of heat exchanger HE is measured with thermometer 2. The gauge pressure of wastewater at outlet of heat exchanger is measured with manometer 5. After leaving the heat exchanger HE , the wastewater passes through a reducing valve RV, which reduced wastewater pressure and when wastewater enters to the separator S, it starts to evaporate. The secondary vapour enters in suction side of mechanical compressor MC, which compresses them to a high pressure. The vacuum pressure of secondary vapour at outlet of separator S is measured with vacuum meter 6. The compressed vapour at discharge side of mechanical compressor MC enters to the plate heat exchange HE, where delivers heat to wastewater. In heat exchanger HE compressed vapour turned to condensate is discharged to condensate tank 9. The temperature of compressed vapour at outlet of mechanical compressor MC is measured with thermometer 3. The vacuum pressure of compressed vapour at outlet of mechanical compressor MC is measured with vacuum meter 7. The mass of condensate is measured by condensate tank 9 and electronic scale.

The operation time of MVR heat pump system (time to collect condensate, produced on the system) is measured by chronometer 11. The atmospheric pressure is measured by barometer 8. The power consumption of electrical energy spent by mechanical compressor MC is measured by wattmeter 10.

Measuring devices and measured parameters of MVR heat pump system are shown in Table 1.

Table 1. Measuring devices and measured parameters of pilot MVR heat pump system

Measuring device	Measured parameter	Designation	Precision measuring	Measuring range
Thermometer 1	Temperature of circulating water at heat exchanger HE inlet	t_{sv}, ºC	1.0 ºC	0-120 ºC
Thermometer 2	Temperature of the circulating water at heat exchanger HE outlet	t_{out}, ºC	1.0 ºC	0-120 ºC
Manometer 5	Water pressure in heat exchanger HE	p_{HE}, kPa	0.1 bar	-1 – 3 bar
Vacuum meter 6	Vacuum pressure of secondary vapour in separator S /suction side of mechanical compressor MC	$p_{v,evap}$, kPa	0.5 kPa	0-100 kPa
Vacuum meter 7	Vacuum pressure of compressed vapour/discharge side of mechanical compressor MC	$p_{v,cond}$, kPa	0.5 kPa	0-100 kPa
Barometer 8	Atmospheric pressure	p_0, kPa	1.0 mmHg	740-780 mm Hg
Water tank 9	Mass of condensate	m, kg	10.0 g	0-10 kg
Chronometer 11	Operation time of MVR heat pump system	τ, s	1 s	0-60 s
Wattmeter 10	Power consumption of electrical energy spent by mechanical compressor MC	N, W	10 W	0-999999.9 kWh

A pilot MVR heat pump system performance is between 5.0 and 16.0 kg/h evaporated water from intake wastewater flow. Absolute evaporating pressure in separator S has values from 15.5 to 25.0kPa. Absolute pressure of compressed vapour at discharge side of mechanical compressor MC has values from 20 to 43kPa. This difference in pressures provides difference between temperature of secondary vapour and temperature of compressed vapour from 5 to 13 K. These pressures (at lack of physical-chemical temperature depression) correspond to saturation evaporation temperature between 55 and 67 ˚C and saturation condensation temperatures between 60 and 78˚C. There is also a temperature difference between 5 and 14 K of temperatures of wastewater in inlet and outlet of plate heat exchanger HE[13]. General appearance of MVR heat pump system is shown on Figure 2.

Fig. 2. General appearance of mechanical vapour recompression heat pump system [7]

3 Analysis and discussion

3.1 Basic equation

The mass flow rate of water circulating through the heat exchanger $\dot{m}_W$ is determined by the factory performance characteristic ($\dot{V}$ -Δp characteristic) of the circulator pump CP, according to the pressure Δp_{CP} :

$$\Delta p_{CP} = p_{HE} - p_{evap}, \tag{1}$$

where: - p_{HE} – absolute pressure of wastewater in heat exchanger HE, kPa;
p_{evap} – absolute pressure of secondary vapour in separator S, kPa.

Heat flux exchanged in the heat exchanger $\dot{Q}$ is determines by the equation of energy balance of wastewater flow rate through heat exchanger HE:

$$\dot{Q} = \dot{m}_W\, c(t_{out} - t_{evap}), \tag{2}$$

where: - $\dot{m}_W$ is mass flow rate of wastewater circulating through the heat exchanger, kg/s;
c – specific heat capacity of the wastewater, specified for wastewater average temperature, kJ/(kg.K);
t_{out} - temperature of wastewater of outlet of heat exchanger HE, ˚C;
t_{evap} - temperature of wastewater of inlet of heat exchanger HE, equal to the evaporation temperature of wastewater in separator S, ˚C.

A mass flow rate of vapour through the mechanical compressor $\dot{m}_K$ can be calculated from the equation of the material balance. It is equal to the mass flow rate of the collected condensate:

$$\dot{m}_K = \frac{m}{\tau} \qquad (3)$$

where: - m - total quantity of condensate collected in the condensate tank, kg;
τ - operation time for collecting the condensate, s.
The process of compression of water vapour in mechanical compressor MC of MVR heat pump system is considered. It is a not isentropic process of compression of real gas - water vapour. The process of compression of water vapour occurs at low absolute pressure (between 15.5 kPa and 43.0 kPa). The compressibility factor of water vapour is calculated by the equation:

$$z = \frac{pV}{RT} \qquad (4)$$

where:- z - compressibility factor, -;
p –absolute pressure of water vapour, MPa;
V –volume of water vapour, m^3;
R –individual gas constant of water vapour, J/(kg.K);
T –absolute temperature of water vapour, K;
The value of compressibility factor in this case is between 0.993 and 0.996, which is very close to 1. In this case vapour can be considered as an ideal gas. Proximate theoretical process to the real process in MVR heat pump system is isentropic compression of ideal gas. In this process submitted specific flow work l_t will match with the defined target function actual coefficient of performance of MVR heat pump system. This work for isentropic process of an ideal gas is calculated by the equation [8]:

$$l_t = \frac{k}{k-1} RT_{evap} \left[1 - \left(\frac{p_{cond}}{p_{evap}} \right)^{\frac{k-1}{k}} \right] \qquad (5)$$

where: - l_t – specific flow work, J/kg;
k – specific heat ratio,-;
R –individual gas constant of water vapour, J/(kg.K);
T_{evap} – absolute temperature of evaporation of wastewater, K;
p_{cond} - absolute pressure of compressed vapour, Pa.
p_{evap} - absolute pressure on secondary vapour in the separator S, Pa .
At lack of physical-chemical temperature depression the value of evaporation temperature of wastewater is equal to temperature of the secondary vapour ($t_{evap} = t_{sv}$).
This relationship is accepted as a basis for mathematical model experiment by converting in form:

$$l = (A_1 t_{sv} + A_2)\sigma^{A_3} \qquad (6)$$

where: - l – actual coefficient of performance, -;
t_{sv} - temperature of secondary vapour, °C;
σ -compression ratio of water vapour in the mechanical compressor MC,-;
A_1, A_2, A_3 – coefficients,-;
From the analysis of this relationship, the following important factors of the actual coefficient of performance l are defined: temperature of secondary water vapour t_{sv} and compression ratio of water vapour in the mechanical compressor MC σ.

Compression ratio of mechanical compressor is calculated by the equation:

$$\sigma = \frac{p_{cond}}{p_{evap}} \tag{7}$$

where: - p_{cond} is absolute pressure of compressed vapour, Pa;
p_{evap} - absolute pressure on secondary vapour in the separator S, Pa.
Guidelines for selecting the relevant factors in the objective function actual coefficient of performance μ gives dependence (8) for the theoretical one μ_{th} [9, 10]:

$$\mu_{th} = \frac{T_{cond}}{T_{cond} - T_{sv}} \tag{8}$$

where: - T_{cond} - thermodynamic temperature of compressed vapour, K;
T_{sv} - thermodynamic temperature of secondary vapour, K.
In this dependence temperatures of compressed and secondary vapour are identified as a saturation temperatures for pressures of compressed and secondary vapour by tables for water and water vapour.
A mathematical model that examined objective function is selected function analogous to (6):

$$\mu = (A_1 t_{sv} + A_2)\sigma^{A_3} \tag{9}$$

Actual coefficient of performance μ is calculated by the equation [4],[5]:

$$\mu = \frac{\dot{Q}}{|N|}, \tag{10}$$

where:- $\dot{Q}$ - heat flux exchanged in heat exchanger, W;
N – power consumption of electrical energy by mechanical compressor MC of MVR heat pump system, W.

3.2. Results

A different sample of industrial wastewater were researched: water from steam boiler blow down, water from CIP (cleaning in place) system of milk factory, water from refrigerant condenser blow down, water from washing vehicles and water from washing a catering equipment. This type of wastewater has low values of organic dry matter. In researched temperature interval no physical-chemical temperature depression was found. Therefore, it is assumed that the evaporation temperature of wastewater is equal to the temperature of the secondary vapour ($t_{evap} = t_{sv}$). With a particular type of waste water, the pilot MVR heat pump system is started and introduced into an established operating mode, including stable maintenance of operating parameters and condensate generation. For a certain period of time the volume of generated condensate is collected and measured.
A classic experiment by two significant factors is conducted. The small number of factors (n = 2) allows the study to be carried out by classical multi-term experiment. A classic full plan of experiment including all recurring combinations of levels of factors is selected. The factors whose influence has been studied are defined: temperature of secondary water vapour in separator S t_{sv} and compression ratio of water vapour in the mechanical compressor MC σ.
The scheme of the experiment is unbalanced with three levels of variation of the temperature of secondary water vapour in separator t_{sv}- 55 ˚C, 60 ˚C, 65 ˚C and five levels of varying of the compression ratio of water vapour in the mechanical compressor MC

σ - 1.30, 1.40, 1.50, 1.60 and 1.70. Levels of variation of two significant factors are also determined by the specific design of pilot MVR heat pump system.
The results of experimental studies are shown in Table 2, Table 3 and Table 4.

Table 2. Experimental data – Study 1

№	t_{sv}	σ	Δp_{CP}	$\dot{m}_W$	t_{out}	$\dot{Q}$	N	μ
	˚C	-	kPa	kg/s	˚C	W	W	-
1	54.7	1.290	165.0	0.175	64.0	6846	680	10.07
2	56.0	1.394	165.0	0.175	63.0	5148	700	7.35
3	55.3	1.500	164.0	0.185	61.0	4390	730	6.01
4	54.7	1.613	165.0	0.175	59.5	3540	750	4.72
5	55.3	1.719	166.5	0.160	60.2	3254	840	3.87
6	60.1	1.300	164.0	0.185	70.0	7685	670	11.47
7	60.6	1.390	164.5	0.180	68.6	6017	700	8.60
8	59.0	1.526	165.0	0.175	66.0	5145	800	6.43
9	59.0	1.632	165.0	0.175	65.0	4410	820	5.38
10	60.1	1.750	164.0	0.185	64.9	3725	880	4.23
11	65.9	1.288	164.5	0.180	80.0	10681	720	14.83
12	65.0	1.400	165.0	0.175	77.0	8823	760	11.61
13	66.7	1.481	165.0	0.175	77.5	7926	800	9.91
14	65.9	1.615	165.0	0.175	75.0	6711	900	7.46
15	65.0	1.712	165.0	0.175	73.5	6252	1100	5.68

Table 3. Experimental data – Study 2

№	t_{sv}	σ	Δp_{CP}	$\dot{m}_W$	t_{out}	$\dot{Q}$	N	μ
	˚C	-	kPa	kg/s	˚C	W	W	-
1	54.7	1.290	165.0	0.175	63.7	6626	680	9.74
2	56.0	1.394	164.0	0.185	62.5	5052	700	7.22
3	55.3	1.500	164.0	0.185	61.0	4390	730	6.01
4	54.7	1.613	165.0	0.175	60.0	3907	820	4.77
5	55.3	1.719	166.5	0.160	60.0	3120	840	3.71
6	60.1	1.300	164.0	0.185	70.2	7840	660	11.88
7	60.6	1.390	164.5	0.180	69.0	6320	700	9.03
8	59.0	1.526	165.0	0.175	66.4	5439	800	6.80
9	59.0	1.632	164.0	0.185	65.4	4971	830	5.99
10	60.1	1.750	164.0	0.185	64.8	3648	850	4.29
11	65.9	1.288	165.5	0.170	81.3	11013	710	15.51
12	65.0	1.400	165.0	0.175	78.0	9558	750	12.74
13	66.7	1.481	164.0	0.185	77.5	8377	800	10.47
14	65.9	1.615	165.0	0.175	75.5	7079	910	7.78
15	65.0	1.712	165.0	0.175	74.0	6619	1080	6.13

Table 4. Experimental data – Study 3

№	t_{sv}	σ	Δp_{CP}	$\dot{m}_W$	t_{out}	$\dot{Q}$	N	μ
	˚C	-	kPa	kg/s	˚C	W	W	-
1	54.7	1.290	165.0	0.175	64.0	6846	690	9.92
2	56.0	1.394	164.0	0.185	63.0	5440	710	7.66
3	55.3	1.500	165.0	0.175	61.0	4154	730	5.69
4	54.7	1.613	165.0	0.175	59.8	3760	810	4.64
5	55.3	1.719	166.5	0.160	60.3	3322	830	4.00
6	60.1	1.300	164.0	0.185	69.6	7374	670	11.01
7	60.6	1.390	164.5	0.180	68.5	5942	660	9.00
8	59.0	1.526	165.0	0.175	66.0	5145	760	6.77
9	59.0	1.632	165.0	0.175	65.1	4484	830	5.40
10	60.1	1.750	165.0	0.175	65.0	3598	860	4.18
11	65.9	1.288	165.5	0.170	81.7	11298	710	15.91
12	65.0	1.400	165.0	0.175	78.0	9558	750	12.74
13	66.7	1.481	164.0	0.185	78.0	8765	820	10.69
14	65.9	1.615	165.0	0.175	75.0	6711	880	7.63
15	65.0	1.712	165.0	0.175	74.0	6619	1060	6.24

Statistical processing of experimental data is made. This includes: checking for homogeneity of variances, check significance of odds betting in the regression equations and check the adequacy of the resulting equations was carried out [11]. A summary experimental data from studies 1, 2 and 3 are shown in Table 5. X_1 and X_2 are significant factors - temperature of secondary water vapour in separator S t_{sv} and compression ratio of water vapour in the mechanical compressor MC σ. $Y_{2,1}$, $Y_{2,2}$, $Y_{2,3}$ are the results of objective function actual coefficient of performance of MVR heat pump, measured three times and Y_2 is respective arithmetical mean value of actual coefficient of performance μ of MVR heat pump.

Table 5. Summary experimental data – Study 1,2 and 3

№	X_1	X_2	$Y_{2,1}$	$Y_{2,2}$	$Y_{2,3}$	Y_2
	˚C	-	-	-	-	-
1	54.7	1.290	10.07	9.74	9.92	9.91
2	56.0	1.394	7.35	7.22	7.66	7.41
3	55.3	1.500	6.01	6.01	5.69	5.90
4	54.7	1.613	4.72	4.77	4.64	4.71
5	55.3	1.719	3.87	3.71	4.00	3.86
6	60.1	1.300	11.47	11.88	11.01	11.45
7	60.6	1.390	8.60	9.03	9.00	8.88
8	59.0	1.526	6.43	6.80	6.77	6.67
9	59.0	1.632	5.38	5.99	5.40	5.59
10	60.1	1.750	4.23	4.29	4.18	4.23
11	65.9	1.288	14.83	15.51	15.91	15.42
12	65.0	1.400	11.61	12.74	12.74	12.36
13	66.7	1.481	9.91	10.47	10.69	10.36
14	65.9	1.615	7.46	7.78	7.63	7.62
15	65.0	1.712	5.68	6.13	6.24	6.02

Objective function actual coefficient of performance obtained equation is as follows:

$$Y_2 = (1.411.X_1 - 56.47)X_2^{-3.27} \quad (11)$$

Regression equation for actual coefficient of performance is obtained by replacing parameters $Y_2 = \mu$, $X_1 = t_{sv}$ and $X_2 = \sigma$:

$$\mu = (1.411 t_{sv} - 56.47)\sigma^{-3.27} \quad (12)$$

In Figure 3 a correlation between objective function actual coefficient of performance and two significant factors: compression ratio and temperature of secondary vapour in separator as a parameter is shown.

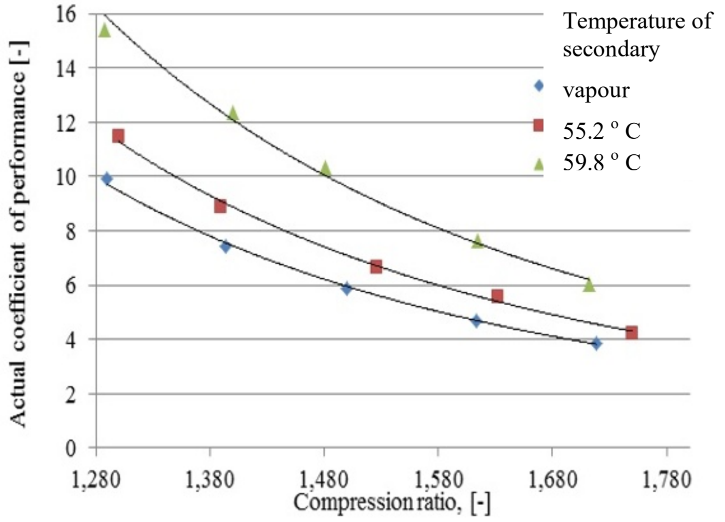

Fig. 3. Correlation between actual coefficient of performance of MVR heat pump system and two independent factors: compression ratio and temperature secondary vapour

In Table 6 a comparison of the values of theoretical μ_{th} and actual coefficient of performance of MVR heat pump system μ are given. The values of theoretical coefficient of performance of MVR heat pump system μ_{th} are calculated by equation (8).

Table 6. Comparison of the values of the theoretical and actual coefficient of performance of MVR heat pump system

t_{sv}	σ	μ_{th}	μ	μ_{th}/μ
°C	-	-	-	-
54.7	1.290	61.5	9.91	6.21
56.0	1.394	47.0	7.41	6.34
55.3	1.500	38.6	5.90	6.54
54.7	1.613	32.8	4.71	6.96
55.3	1.719	28.9	3.86	7.49
60.1	1.300	58.8	11.45	5.14
60.6	1.390	46.8	8.88	5.27
59.0	1.526	36.6	6.67	5.49
59.0	1.632	31.6	5.59	5.65
60.1	1.750	27.5	4.23	6.50
65.9	1.288	59.5	15.42	3.86
65.0	1.400	44.9	12.36	3.63
66.7	1.481	38.0	10.36	3.67
65.9	1.615	31.2	7.62	4.09
65.0	1.712	27.7	6.02	4.60

4 Conclusions

The analysis of graphic dependencies (Fig.3) and equation (12) show that actual coefficient of performance in pilot MVR heat pump system μ highly depends of the compression ratio of water vapour in mechanical compressor MC σ. The relation between these two variables in the study area is inverse speed dependence with negative exponent value A_3 = - 3.27.
Less dependence on actual coefficient of performance μ proves temperature of secondary vapour t_{sv}. It is linear proportional correlation between actual coefficient of performance μ and temperature of secondary vapour t_{sv} because of positive value of coefficient A_1 = 1.411.
In researched interval values of actual coefficient of performance of MVR heat pump system μ are between 3.86 and 15.42, and the theoretical one μ_{th} - from 3.63 to 7.49 times greater. As a result, it can conclude that pilot MVR heat pump system, in order to operate with high values of the actual coefficient of performance μ should be working to high values of temperatures of secondary vapour t_{sv} and low values of compression ratio of water vapour in mechanical compressor σ.

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