

# Power Production Evaluation from Residual Industrial Heat

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**ABSTRACT:** In this study, the power generation evaluation from residual industrial heat were analyzed using source heat temperature (150-225) °C and mass flow rate of heat source about 300 kg/s. A mathematical model was developed according to turbine and pump power as well as the heat add and rejected from the evaporator and condenser with regard to the ambient temperature effects and superheated temperature effects on the performance of Rankine cycle system. The performance of the system was evaluated under six working fluids (Ammonia, Propane, Water, Benzene, R245fa and n-pentane) divided between wet and dry fluids. Can be seen from result that the superheated temperature is good effects for wet fluids but is bad effects on dry fluids which is the net power and thermal efficiency increasing with increase the superheated temperature. Also for produce more power from the Rankine cycle system we need more heat source. As well as the effect of increasing of ambient temperature on the performance of Rankine cycle system is bad especially in summer session. The value of thermal efficiency was between 7.46 and 21.4 for the six fluids selected. Water was the better performance between all working fluids selected. Finally the results is compared with the literature and the agreement is good.

**KEYWORDS:** Rankine cycle system , Power production , Residual industrial heat.

## I. INTRODUCTION

The percentage of heat losses from industrial sector is very big about 60-70 % from total heat source to the manufactory so, this percentage invite us to thinking about reduce the value of percentage and recover heat to production power. The subject of power production is very important because of the increasing requirements for the consuming energy in all communities. At the boiler exit for the electric power station the temperature of exhaust gases usually exceed 500°C as well as the temperature of the products from the internal combustion chamber [1].

There are some papers Dealt with the subject of regain of the dissipation heat. A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power proposed and analyzed by Chen et al. [2]. Guo et al. [3] compared the net power output of CO<sub>2</sub>-based transcritical Rankine cycle and R245fa-based subcritical ORC with low temperature geothermal source.

From a fairly alternate point of view, Labrecque and Goni Boulama [4] have exhibited a general technique of assessing the force era capability of warm liquid streams of various temperatures and natures.

Guopeng Yu demonstrates that, around 75% and 9.5% of waste heat from exhaust gases and from cooling water individually can be recuperated under the motor conditions extending from high load to low load [5].

The investigation of Mr. M. Bianchi demonstrates that the most noteworthy electric productivity values, more than 20% with reference to the information heat substance, are gotten with the Organic Rankine Cycle, while not immaterial estimations of effectiveness (up to 10%) are achievable with the Inverted Brayton Cycle, if the accessible temperature is higher than 400 °C [6].

The effect of parameters of a novel combined power and ejector refrigeration cycle on the net power output is investigated by Dai et al. [7]. the system performance analysis and optimization of ORC with R245fa is explored by Wei et al. [8] as well as they found that it was a good way to improve the net power output of the system by maximizing the benefits of the waste heat as much as possible.

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This paper focus on investing the residual industrial heat and converted it to useful power energy through Rankine cycle system. The effect of ambient temperature and superheated temperature on the net power and thermal efficiency of the Rankine cycle system are discussed for six working fluid selected (Ammonia, Propane, Water, Benzene, R245fa and n-pentane).

## II. SYSTEM DESCRIPTION

As appeared in Figure 1, the Rankine cycle system utilized as a part of this paper is made out of a turbine, condenser, an evaporator (heat recovery unit), a working liquid pump and other assistant equipment. The heat source, for our situation the residual industrial heat, is pumped into the evaporator (process 1-2), where the working liquid is evaporated, then conveyed to the turbine (process 2-3). The working liquid drives the turbine to produce power (process 3-4), alongside pressure and temperature diminishes. The low pressure and temperature of working liquid is cooled to fluid state when going through the condenser (process 4-1) and gathered in the beneficiary. The working liquid pump drives the fluid refrigerant once more into the evaporator (process 1-2), to again ingest heat, then the above procedure repeats.

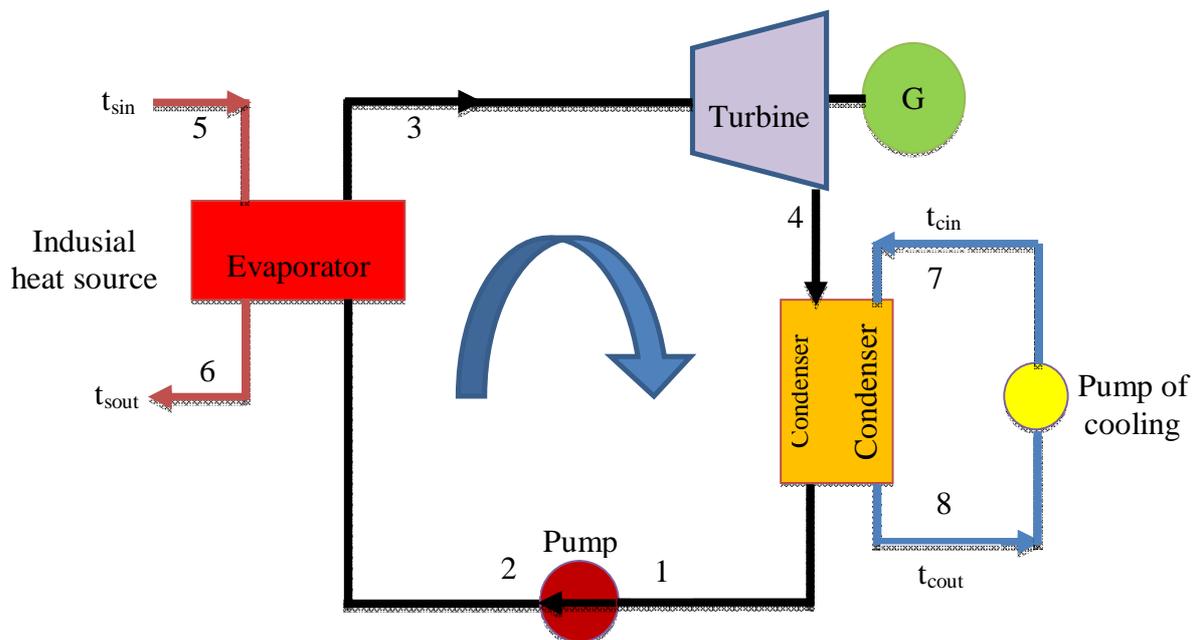


Fig.1. Schematic of a Rankine power cycle.

Figure 2 (a to f) shows a typical T-S diagram for six working fluids: Ammonia, Propane, Water, Benzene, R245fa and n-pentane. The diagrams drawn by EES program. The six working fluid used in model distributed Between wet and dry fluids to see the comparison between them.

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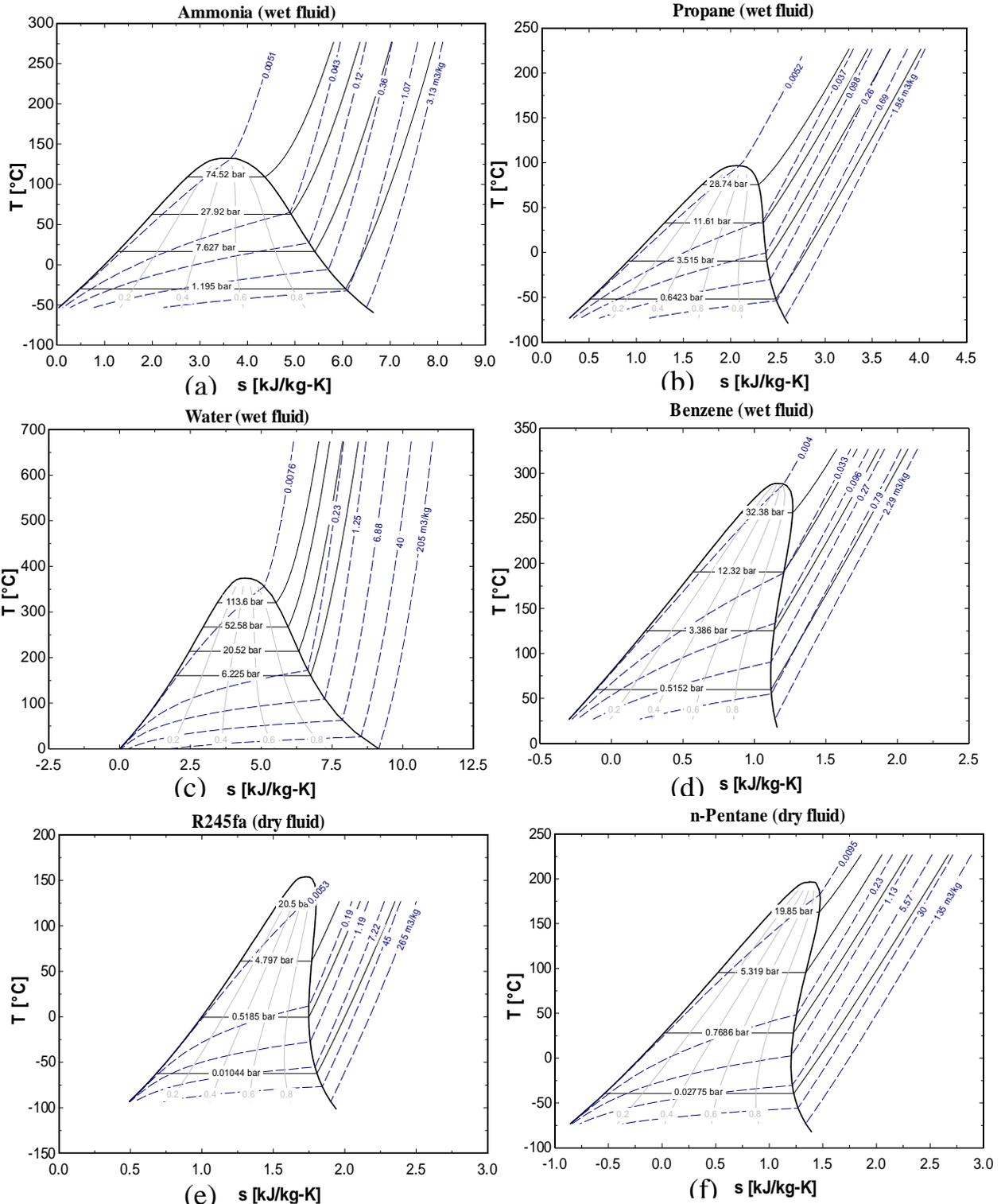


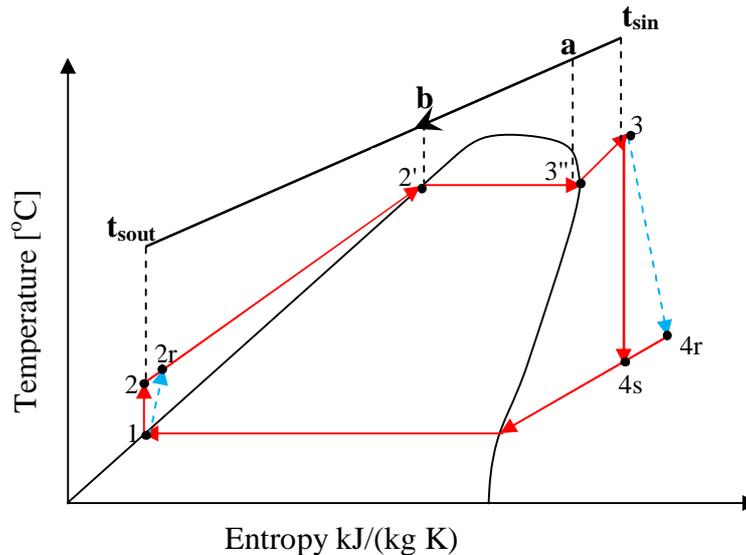
Fig.2. A typical T-S diagram for working fluids.

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Figure 3 shows the T-S diagram for Rankine cycle system and as shown  $T_{sin}$  represent the inlet source temperature,  $T_{sout}$  represent the outlet source temperature, a,b represent the med points for the source temperature. Table 1 represent the input data used for model.



Process	Description
1-2	Pump (isentropic)
1-2r	Pump (real process)
2r-2'	Evaporator (Preheater zone)
2'-3''	Evaporator (Boiler zone)
3''-3	Evaporator (Superheater zone)
3-4r	Turbine (real process)
3-4s	Turbine (isentropic)
4s-5	Condenser(Desuperheater zone)
5-1	Condenser (Condensation zone)

**Fig.3.** T-S diagram of the ORC simple configuration.

Table 1. Main input data for the model.

Parameter	Specification	Value	Units
Source mass flow rate	$\dot{m}_s$	300	kg/s
Inlet source temperature	$t_{sin}$	150-250	° C
Outlet source temperature	$t_{sout}$	130	° C
Ambient temperature	$t_{amb}$	24	° C
Pumpefficiency	$\eta_p$	0.9	—
Expander efficiency	$\eta_{ex}$	0.9	—

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## III. MATHEMATICAL MODEL

In this paragraph the processes of Rankine cycle system can be described as follows:

Process 1 to 2:

This process across pump which is the pressure of working fluid will increase to the evaporator pressure. The pump power will determine as follows [9, 10]:

$$P_{p, \text{actual}} = \frac{P_{p, \text{ideal}}}{\eta_p} = \frac{\dot{m}_f (h_1 - h_{2s})}{\eta_p} = \dot{m}_f (h_1 - h_{2r}) \quad (1)$$

Where  $P_{p, \text{ideal}}$  is the power of pump in ideal case,  $P_{p, \text{actual}}$  is the power of pump in actual case,  $\eta_p$  is the pump efficiency,  $\dot{m}_f$  is the mass flow rate of working fluid,  $h_1$ ,  $h_{2s}$ ,  $h_{2r}$  are the enthalpy of the point 1, 2s and 2r respectively as shown in Figure 3.

From the following equation, the enthalpy of point 2r can be calculated depending on pump efficiency:

$$h_{2r} = h_1 + \frac{h_2 - h_1}{\eta_p} \quad (2)$$

Depending on the enthalpy and evaporation pressure of point 2r, the entropy and temperature can be obtained. Also, the inlet turbine temperature can be calculated, as follows:

$$t_3 = t_{ev} + \Delta t_{sp} \quad (3)$$

Where  $t_{ev}$  is the evaporation temperature (saturation temperature) at evaporator pressure which was estimated in the first step and  $\Delta t_{sp}$  is the superheating degree over the evaporation temperature.

Process 2 to 3:

This process takes place in the evaporator which is constant pressure heat absorption. The heat transferred from the residual industrial heat to the working fluid is:

$$\dot{Q}_{ev} = \dot{m}_f (h_3 - h_2) \quad (4)$$

Where  $h_2$  and  $h_3$  are the enthalpies of point 2 and 3 respectively.

Process 3 to 4:

The production power will be in this process and the turbine power is determined as follows:

$$P_{t, \text{actual}} = P_{t, \text{ideal}} \eta_t = \dot{m}_f (h_3 - h_4) \eta_t = \dot{m}_f (h_3 - h_{4r}) \quad (5)$$

Where  $P_{t, \text{ideal}}$  is the power of turbine in ideal case,  $P_{t, \text{actual}}$  is the power of turbine in actual case,  $\eta_t$  is the turbine efficiency,  $h_3$ ,  $h_4$ ,  $h_{4r}$  are the enthalpy of the point 3, 4 and 4r respectively as shown in Figure 3.

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Process 4 to 1:

This process takes place in the condenser which is constant pressure heat reject. The heat transferred from the working fluid to the heat sink at the condenser is:

$$\dot{Q}_{con} = \dot{m}_f (h_4 - h_1) \quad (6)$$

The net power of the Rankine system is calculated as:

$$P_{net} = P_{t,actual} - P_{p,actual} \quad (7)$$

The thermal efficiency is defined as the ratio between the power net of the cycle to the heat addition (across evaporator). It can be expressed as:

$$\eta_{th} = \frac{P_n}{\dot{Q}_{ev}} = \frac{P_{t,actual} - P_{p,actual}}{\dot{Q}_{ev}} \quad (8)$$

## IV. TEST OF MODEL

It was necessary to check the mathematical modeling before proceeding with the results. The present model and calculation procedure were successfully validated by comparing their results with corresponding results from literature, especially with those of Author: T.Q. Nguyen [11] and the comparison shows a very good agreement as shown in Table 2.

**Table 2.** Validation of the numerical model with the previously published data [11]

Fluid	Evaporation pressure (P <sub>ev</sub> )(bar)	Evaporation temperature (T <sub>ev</sub> )(°C)	Thermal efficiency (η <sub>th</sub> ) (%)	Net Power (P <sub>net</sub> ) (KW)	Condenser pressure (P <sub>con</sub> )(bar)	Reference
<b>Benzene</b>	3.79	130	17.00	5900	0.199	Present
<b>Benzene</b>	3.79	130	18.00	5564	0.197	[11]
<b>n-heptane</b>	6.96	180.8	20.41	6278	0.0777	Present
<b>n-heptane</b>	6.96	180.8	20.8	6285	0.0761	[11]

## V. RESULTS AND DISCUSSION

A program was created to evaluating the Rankine cycle system performance in EES program according to the established mathematical model. Table 3 shows many parameters such as evaporation pressure, evaporation temperature, thermal efficiency, net power and working fluid mass flow rate according to type of working fluid under some of input data as follows:

T<sub>sin</sub>=225 °C , T<sub>sout</sub>=130°C , Q<sub>add</sub>=30758 KW , t<sub>amb</sub>=24°C , m<sub>s</sub>=300 kg/s , T<sub>superheated</sub>=10°C.

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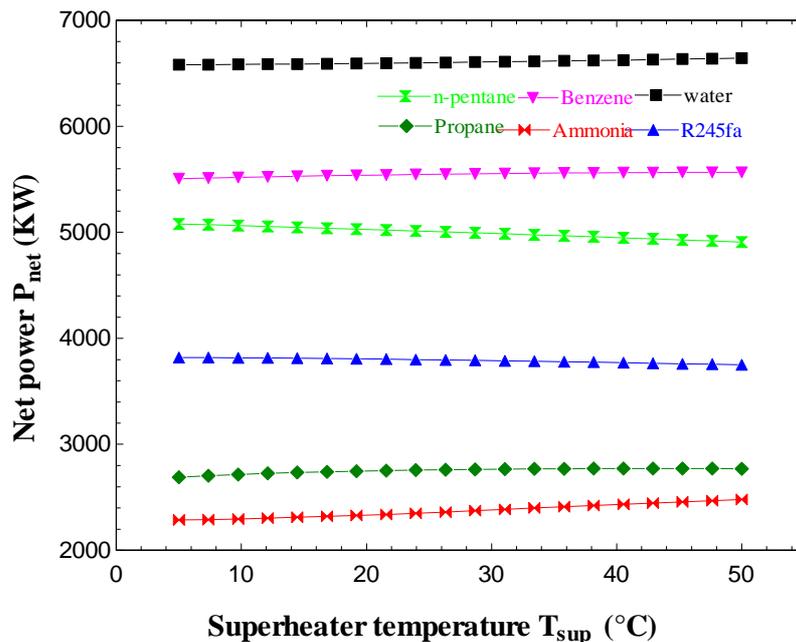
**Table 3.** Some of parameters for specified working fluids.

Fluid	Evaporation pressure ( $P_{ev}$ )(bar)	Evaporation temperature ( $T_{ev}$ )(°C)	Thermal efficiency ( $\eta_{th}$ ) (%)	Net Power ( $P_{net}$ ) (KW)	Working fluid mass flow rate ( $m_f$ ) (kg/s)
<b>Water</b>	3	133.6	21.4	6583	11.72
<b>Benzene</b>	3	120	17.94	5518	55.99
<b>R245fa</b>	10	89.6	12.4	3816	127.2
<b>n-pentane</b>	10	125	16.46	5062	57.2
<b>Ammonia</b>	25	58.17	7.46	2297	25.86
<b>Propane</b>	25	68.26	8.83	2716	80.79

As shown in Table 3 according to using type of fluid and under the value of evaporation pressure the thermal efficiency and the net power are evaluated as well as the mass flow rate of working fluid. It is clear from the table the thermal efficiency and the net power of the water is larger than Benzene under the same pressure. In another hand the n-pentane is better than R245fa under the same pressure and Ammonia is better than propane. As over all the water is the best efficiency and net power production and follows by Benzene and n-pentane etc.

### 1. Effect of superheated temperature

In Figure 4, it can also be seen that the slope of the net power generation curve associated with the superheated temperature. From the figure wet fluids such as water, Ammonia and Benzene the power production is increases with superheated temperature but the dry fluids such as n-pentane and R245fa the power production is decreases with superheated temperature. Therefore we prefer the superheated with wet fluid to increase the efficiency and the net power of the system but for dry fluids the superheated have a bad effects.



**Fig.4.** Effect of superheated temperature on the net power of the system.

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Figure 5 shows the efficiency of working fluids with superheated temperature and it is clear that the efficiency for wet fluids is increases with superheated temperature and for dry fluids is decreases. From this figure we can conclude that the superheated is good only for the wet fluids.

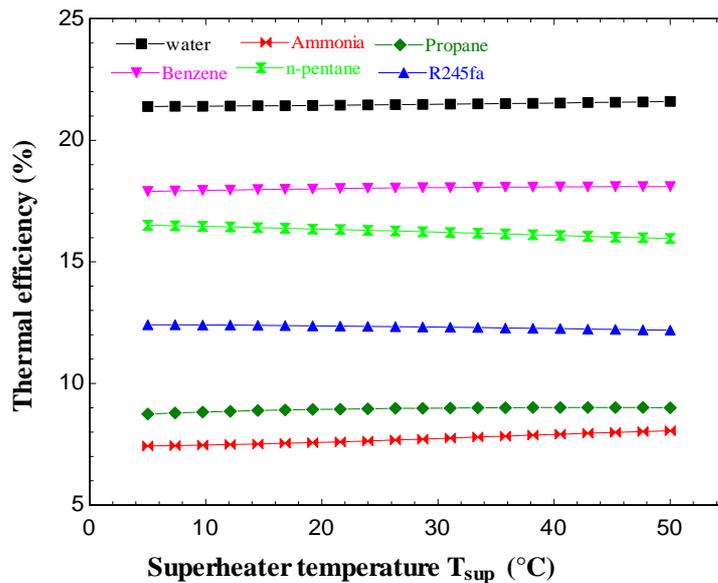


Fig.5. Effect of superheated temperature on the thermal efficiency of the system

## 2. Effect of ambient temperature

The effect of ambient temperature on the performance of power production system for many working fluids is shown in Figure 6. It is clear from Figure that the net power is decreases when the ambient temperature is increases and that's happen in the summer session. Also, it can see the decreasing in net power is large with increasing the ambient temperature in summer session for all working fluids which is select in our analysis.

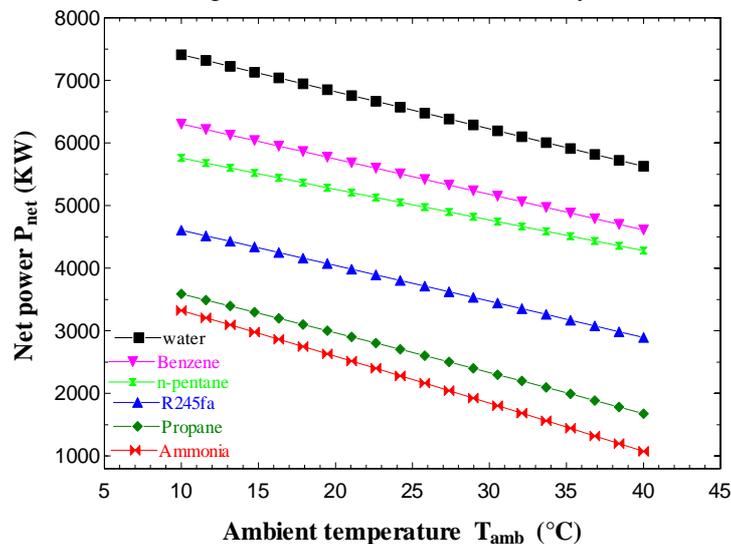


Fig. 6. Effect of ambient temperature on the net power of the system.

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Also, the thermal efficiency of the Rankine cycle system is decreases with increasing the ambient temperature through the summer session for all working fluid which is select to using in our analysis as shown in Figure 7. From this figure we can conclude that the ambient temperature increasing effects on the performance of the system is bad.

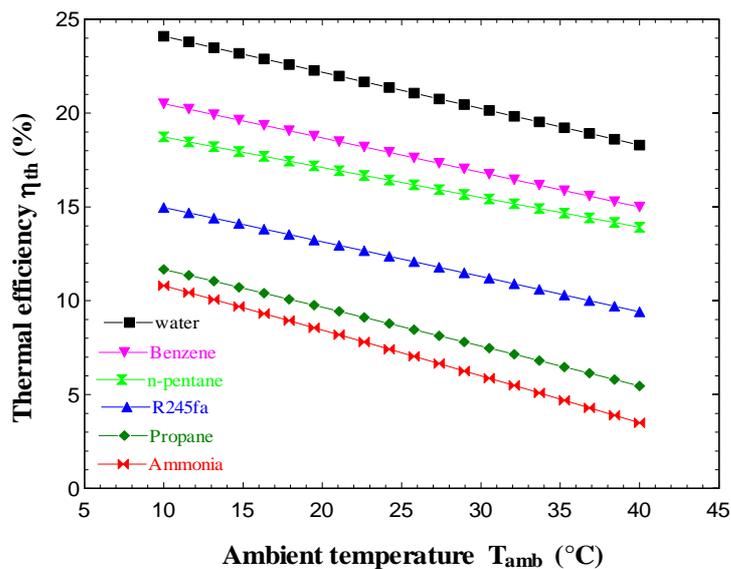


Fig.7. Effect of ambient temperature on the thermal efficiency of the system.

### 3. Effect of the source temperature

In Figure 8 the effect of source temperature on the net power production in the system is represented. It is clear that the net power of the system is increases when the source heat temperature is increases. Therefore the net power production is large when the source heat temperature is large and vice versa. In the same time the sharp increasing in net power production for water but the low increasing for Ammonia.

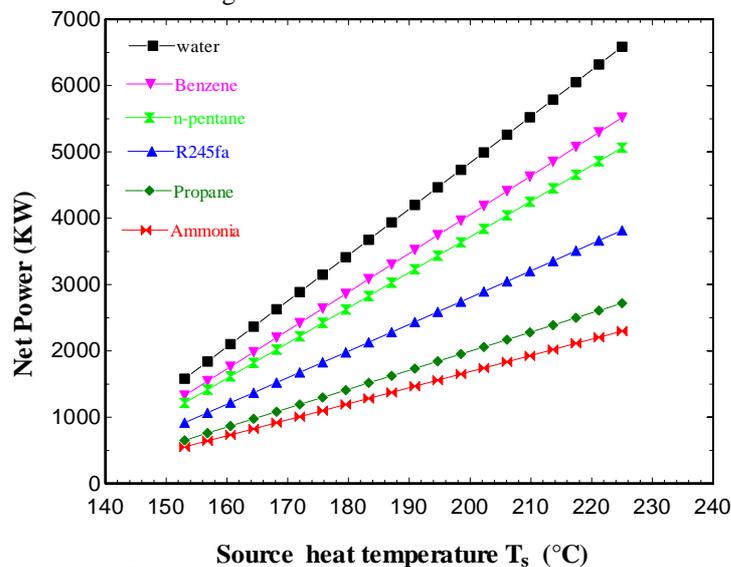


Fig.8. Effect of source temperature on the net power of the system.

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## VI. CONCLUSIONS

The steady state of theoretical modelling for production power from residual industrial heat using the Rankine cycle was examined and presented in this study. The heat source temperature used in this analysis is 150-250 °C and the mass flow rate of source heat is 300 kg/s. There are some of conclusions from the study as follows:

1. The superheated temperature is good effects for wet fluids but is bad effects on dry fluids which is the net power and thermal efficiency increasing with increase the superheated temperature.
  2. For produce more power from the Rankine system we need more heat source.
  3. Effect of increasing of ambient temperature on the performance of Rankine system is bad especially in summer session.
  4. The value of thermal efficiency was between 7.46 and 21.4 for six fluids.
- Water was the better performance between all working fluids selected.

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