A Comparison between the Use of Different Working Fluids in an Application of Tesla Turbine and Centrifugal Turbine in Organic Rankine Cycle

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Abstract

This paper aims to compare the use of Isopentane, Refrigerant 22 (R22) and Refrigerant 134a (R134a) as working fluids expanding in an application of *Tesla turbine* and *Centrifugal Turbine* in Organic Rankine Cycle (ORC). The working fluid has a fixed point below boiling water and works in low-temperature sources between 80-120 °C which can be produced from waste heat, solar-thermal energy and geothermal energy. The experimenton ORC using Tesla turbine and Centrifugal Turbine reveals that the suitability of high pressure pump for working fluid affected their efficiency. The result of the experimentand calculation of ORC using (1) *Isopentane* efficiency is 30% better than R22 and R134a estimate, and (2) *Turbine* efficiency is better than *Tesla turbine* at 28%. It should be noted that Tesla turbine is much cheaper and easily structured than other turbines which can be applied on Organic Rankine Cycle Machine. Further studies could deal with cost and efficiency.

Keywords: *Tesla turbine, organic rankine cycle, low-temperature sources, flow rate, high pressure pump*

1. Introduction

At present, people around the world are concerned with energy and environment issues, and various countries are entering into the age of energy shortage and climate change. These incidents have stemmed from excessive consumption on fossil fuel in developing infrastructure and supporting economic growth. However, people have recognized criticality of energy and environmental problems, and thus have tried to find practical solutions for sustainable development. Yamamoto et al (2001) suggested the use of renewable energy that is friendly to the environment. Solar energy, therefore, has become a choice to generate electricity for its low cost and efficiency (Wikipedia, 2009). The use of *Organic Rankine Cycle* with thermal energy storage system can produce electricity with a lower cost than that of conventional oil.

The Organic Rankine Cycle (ORC) works in low-temperature sources between 80-120 °C. Thus, it is produced from various natural and renewable sources such as geothermal energy, waste heat, and solar-thermal energy to generate electricity (Tchanche et al., 2009). The Organic Rankine Cycle consists of (1) solar collector, (2) thermal energy storage system and (3) Organic Rankine Cycle power system with a comparison on the use of Isopentane and Refrigerant 22 as working fluids and (4) turbine expander for shaft work (Thawichsri & Nilnont, 2016).

2. Theory

The actual heat transfer may be computed by calculating either the energy loss by hot fluid or the energy or the cold fluid, as shon in equation (1) (Cengel, 1998; Holman, (2001).

$$q_H = \dot{m}C_p(T_{in} - T_{out}) \qquad (1)$$

2.1 Rankine Cycle: The Ideal Cycle for Vopor Power Cycle

Many impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser, as shown schematically on a T-s diagram and a P-h diagram in Figure 1. The resulted cycle is the Rankine cycle, which is the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes (Cengel, 1998):

Figure 1: P-h diagram of the Rankine cycle
1-2 Isentropic compression in a pump
3-4 Isentropic expansion in a turbine
4-1 Constant pressure heat rejection in a condenser
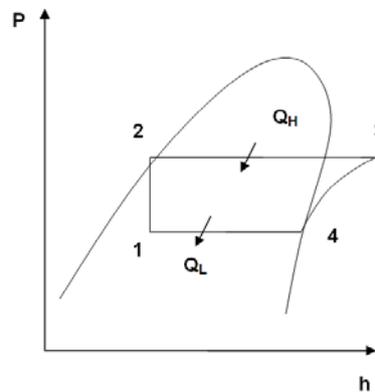
Energy Analysis of the Ideal Rankine Cycle

All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected (Cengel, 1998). Then the steady-flow energy equation per unit mass of steam is reduced to

$$(q_{in} - q_{out}) + (W_{in} - W_{out}) = h_e - h_{in} \qquad (2)$$

The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic. Then the conservation of energy relation for each device can be expressed as follows:

Pump	$(q = 0)$:	$W_{pump,in} = h_2 - h_1$	(3)
Boil	$(W = 0)$:	$q_{in} = h_3 - h_2$	(4)
Turbine	$(q = 0)$:	$W_{turbine,out} = h_3 - h_4$	(5)
Condenser	$(W = 0)$:	$q_{out} = h_4 - h_1$	(6)

The thermal efficiency of the Rankine cycle is determined from

$$\eta_{the} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{in}}{q_{out}}$$

(7)

Where

$$W_{net} = q_{in} - q_{out} = W_{turb} - W_{pump,in}$$

2.2 Determination of Power from Torque and Angular Speed

Apart from the direct measurement of power, it can also be calculated from equation (8) once the torque and angular velocity are known.

$$P = \tau\omega$$

(8)

In the paper of Design of Tesla Turbine, the reference to the change in speed of the mechanism becomes very flexible (Cairns, 2003; Thawichsri & Nilnont, 2016). Mr. Tesla claimed that the total effectiveness of his turbine could reach up to 98% (Rice, 2003). Professor Warner Rice tried to renew Tesla's experiments. He used pressure air as a work substance. He reached a total effectiveness between 36% and 41% through his experiment. He published a mimeograph titled "Tesla Turbomachinery" in 1990, where he specified that effectiveness of the rotor could be very high (up to 95%) with the effect of laminar flow (Rice, 2003).

The most important parameters that affect the performance and efficiency of disc turbomachinery (Cengel, 1998), as outlined by Cairns (Holman, 2001) and Rice (2003) are as follows:

(a) spacing between the discs;
(b) characteristics of the fluid and the flow, such as velocity ratio;
(c) conditions of the surfaces of the disc and radius ratio;
(d) radial and axial clearances between the rotor and the housing.

3. Nomenclature

|			
q_H	heat transfer at moment [W],	$\dot{m}$	mass flow rate [kg/s]
c_p	specific heat capacity [kJ/kg K],	T_{in}	temperature inlet [°C]
T_{out}	temperature outlet [°C],	h_e	specific enthalpy at exit [kJ/kg]
h_i	specific enthalpy [kJ/kg],	W	work [W]
η_{th}	thermal efficiency		

4. Equipment and Data Collecting Position

Figure 2: The Organic Rankine Cycle system and data collecting position
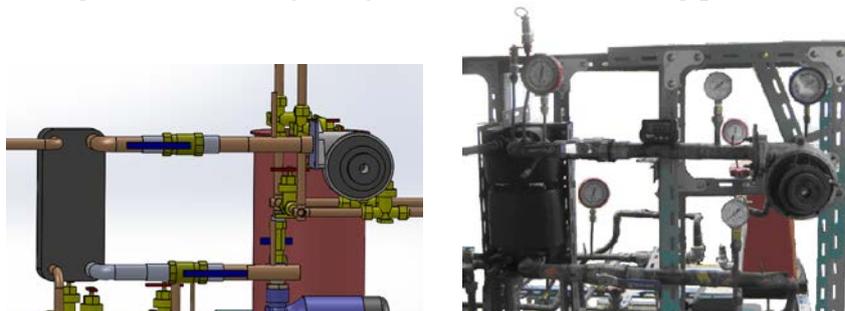
Figure 3: The Diagram of Organic Rankine Cycle System and Data Collecting Position
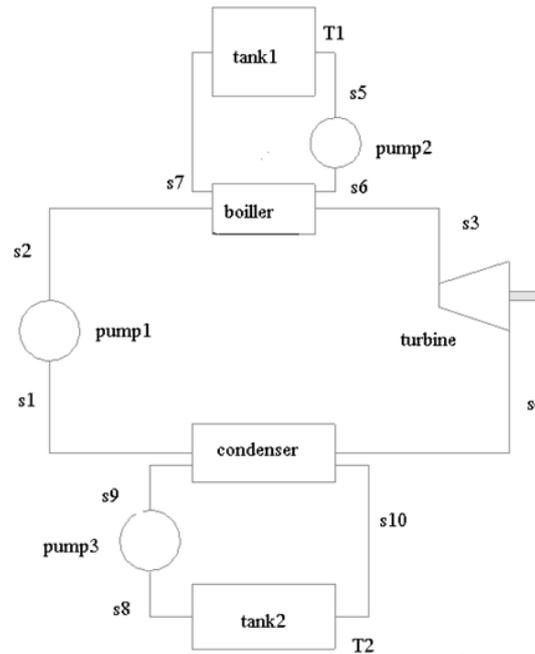
4.1 Experiment Methods, the use of Isopentane as working fluid expanding.

1. Preparing the water in a hot water storage tank at temperature 90 °C.
2. Opening water valve the hot water storage tank sends the hot water flows to reach inside boiler.
3. Opening working fluid valve expanded through Centrifugal Turbine.
4. Recording data saving follow all position.
5. Starting steps 1 to 4 again by change temperatures in the hot water storage tank at temperature 80 and 70 °C, respectively.
6. Starting steps 1 to 5 again by changing Tesla Turbine in the system at temperature 90, 80 and 70 °C, respectively.

4.2 Experiment Methods, the Use of Refrigerant 22 as Working Fluid Expanding

1. Preparing the water in a hot water storage tank at temperature 90 °C.
2. Opening water valve the hot water storage tank sends the hot water flows to reach inside boiler.
3. Opening working fluid valve expanded through Centrifugal Turbine.
4. Recording data saving follow all position.
5. Starting steps 1 to 4 again by change temperatures in the hot water storage tank at temperature 80 and 70 °C, respectively.
6. Starting steps 1 to 5 again by changing Tesla Turbine in the system at temperature 90, 80 and 70 °C, respectively.

4.3 Experiment Methods, the Use of Refrigerant 134a as Working Fluid Expanding

1. Preparing the water in a hot water storage tank at temperature 90 °C.
2. Opening water valve the hot water storage tank sends the hot water flows to reach inside boiler.

3. Opening working fluid valve expanded through Centrifugal Turbine.
4. Recording data saving follow all position.
5. Starting steps 1 to 4 again by change temperatures in the hot water storage tank at temperature 80 and 70 °C, respectively.
6. Starting steps 1 to 5 again by changing Tesla Turbine in the system at temperature 90, 80 and 70 °C, respectively.

**Figure 4:** Tesla Turbine Plate of the Experiment

5. Results and Discussion

5.1 Experiment Methods, the Use of Isopentane as Working Fluid Expanding

The theory for calculation, Organic Rankine Cycle, using heat source at temperatures 90, 80 and 70 °C, respectively. Calculation is by approximation from the experiment and comparison with P-h and T-s Diagram of a working fluid, as follows.

Figure 5: P-h and T-s diagrams of isopentane application for Organic Rankine Cycle
  -Red line using heat source at temperatures 90 °C
  -Blue line using heat source at temperatures 80 °C
  -Green line using heat source at temperatures 70 °C
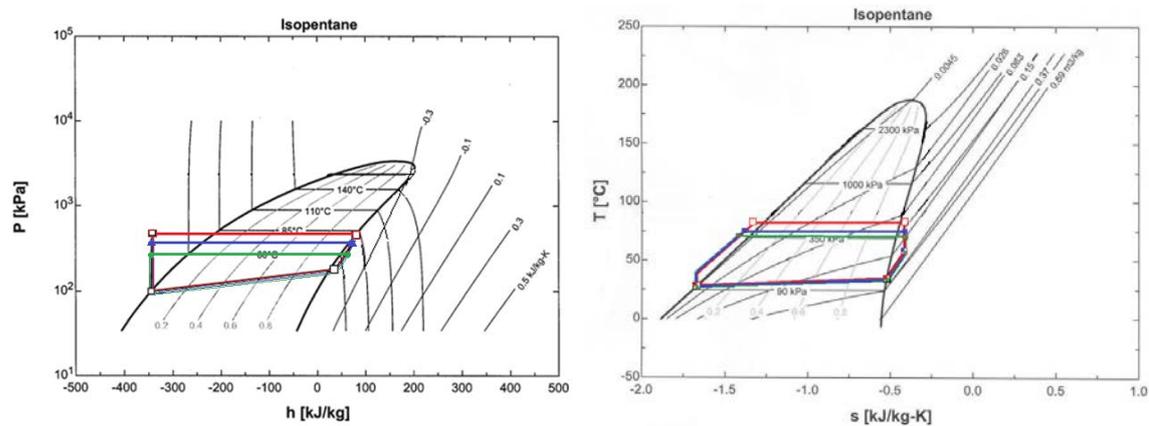
Results (Tesla Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 6 bar and 80 °C, respectively, at pressure and temperature outlet state 1 bar and 30 °C, respectively. The output power was 35 kJ/kg and the thermal efficiency equaled 8.3%.

The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted the working fluid through turbine at pressure and temperature inlet state 5 bar and 70 °C,

respectively, at pressure and temperature outlet state 1 bar and 30 °C, respectively. The output power was 24.5 kJ/kg and the thermal efficiency equaled 6.2%.

The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 4 bar and 60 °C, respectively, at pressure and temperature outlet state 1 bar and 30 °C, respectively. The output power was 14 kJ/kg and the thermal efficiency equaled 3.6%.

Results (Centrifugal Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 6 bar and 80 °C, respectively, at pressure and temperature outlet state 1 bar and 30 , respectively. The output power was 50 kJ/kg and the thermal efficiency equaled 11.9%.

The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 5 bar and 70 °C, respectively, at pressure and temperature outlet state 1 bar and 30 °C, respectively. The output power was 35 kJ/kg and the thermal efficiency equaled 8.6%.
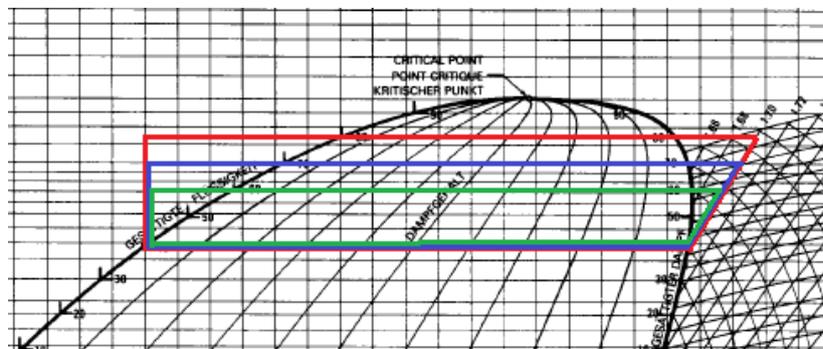
The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 4 bar and 60 °C, respectively, at pressure and temperature outlet state 1 bar and 30 °C, respectively. The output power was 20 kJ/kg and the thermal efficiency equaled 5.1%.

5.2 Experiment Methods, the Use of Refrigerant 22 (R22) as Working Fluid Expanding

The theory for calculation, Organic Rankine Cycle, using heat source at temperatures 90, 80 and 70 °C, respectively. Calculation is by approximation from the experiment and comparison with P-h Diagram of a working fluid, as follows.

Figure 6: P-h diagram of R22 application for Organic Rankine Cycle
-Red line using heat source at temperatures 90 °C
-Blue line using heat source at temperatures 80 °C
-Green line using heat source at temperatures 70 °C

Results (Tesla Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 37 bar and 80 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °C, respectively. The output power was 15.4 kJ/kg and the thermal efficiency equaled 8.5 %.

The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 29 bar and 70 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °C, respectively. The output power was 9.1 kJ/kg and the thermal efficiency equaled 5.0 %.

The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 15 bar and 60 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °C, respectively. The output power was 4.2 kJ/kg and the thermal efficiency equaled 2.3 %.

Results (Centrifugal Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 37 bar and 80 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °C, respectively The output power was 20 kJ/kg and the thermal efficiency equaled 12 %.
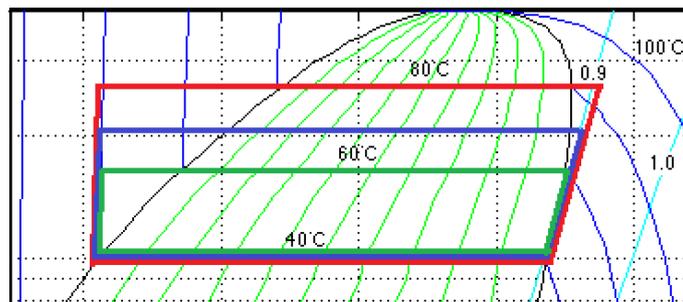
The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 29 bar and 70 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °C, respectively. The output power was11.83 kJ/kg and the thermal efficiency equaled 7.1 %.

The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 15 bar and 60 °C, respectively, at pressure and temperature outlet state 15 bar and 40 °, respectively. The output power was 6 kJ/kg and the thermal efficiency equaled 5.5 %.

5.3 Experiment Methods, the Use of Refrigerant 134a (R134a) as Working Fluid Expanding

The theory for calculation, Organic Rankine Cycle, using heat source at temperatures 90, 80 and 70 °C, respectively. Calculation is by approximation from the experiment and comparison with P-h Diagram of a working fluid, as follows.

Figure 7: P-h diagram of R134a application for Organic Rankine Cycle
-Red line using heat source at temperatures 90 °C
-Blue line using heat source at temperatures 80 °C
-Green line using heat source at temperatures 70 °C

Results (Tesla Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 26.5 bar and 80 °C, respectively, at pressure and temperature outlet state 10 bar and 40 °C, respectively. The output power was 14 kJ/kg and the thermal efficiency equaled 7.57 %.

The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 20.8 bar and 70 °C, respectively, at pressure and temperature outlet state 10 bar and 40 °C, respectively. The output power was 9.8 kJ/kg and the thermal efficiency equaled 5.74 %.

The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resuled in the working fluid through turbine at pressure and temperature inlet state 17.2 bar and 60 °C, respectively, at pressure and temperature outlet state 10 bar and 40 °, respectively, The output power was 5.6 kJ/kg and the thermal efficiency equaled 3.23 %.
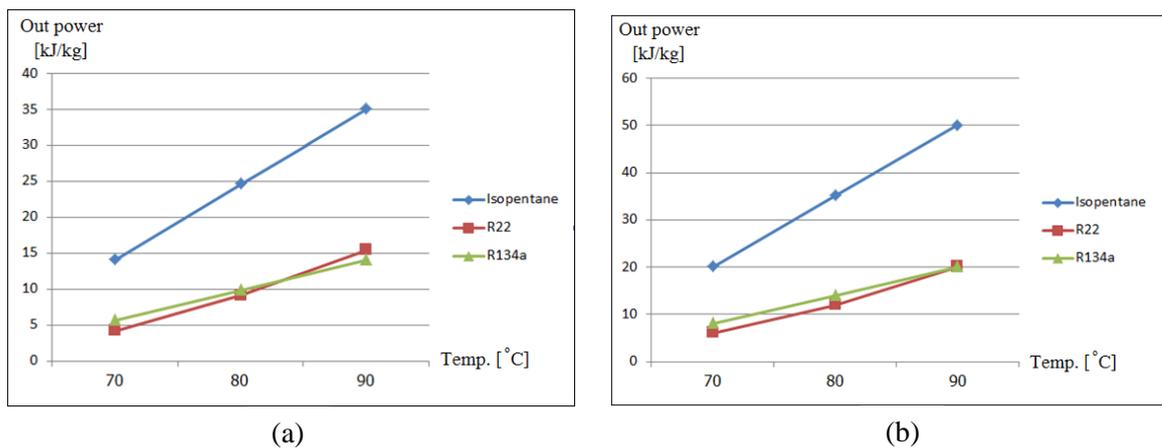
Results (Centrifugal Turbine)

The Organic Rankine Cycle system, using heat source at temperatures 90 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 26.5 bar and 80 °C, respectively, at pressure and temperature outlet state 10 bar and 30 °C, respectively. The output power was 20 kJ/kg and the thermal efficiency equaled 10.81 %.

The Organic Rankine Cycle system, using heat source at temperatures 80 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 20.8 bar and 70 °C, respectively, at pressure and temperature outlet state 10 bar and 30 °C, respectively. The output power was 14 kJ/kg and The thermal efficiency equaled 7.82 %.

The Organic Rankine Cycle system, using heat source at temperatures 70 °C, resulted in the working fluid through turbine at pressure and temperature inlet state 17.2 bar and 60 °C, respectively, at pressure and temperature outlet state 10 bar and 30 °C, respectively. The output power was 8 kJ/kg and The thermal efficiency equaled 4.62 %.

Figure 8: Result of Out Power on Isopentane, Refrigerant 22 and Refrigerant 134a
(a) Result of Tesla Turbine.
(b) Result of Centrifugal Turbine.

(a)   (b)

Figure 9: Result of Efficiency on Isopentane, Refrigerant 22 and Refrigerant 134a
(a) Result of Tesla Turbine.
(b) Result of Centrifugal Turbine.

(a)   (b)
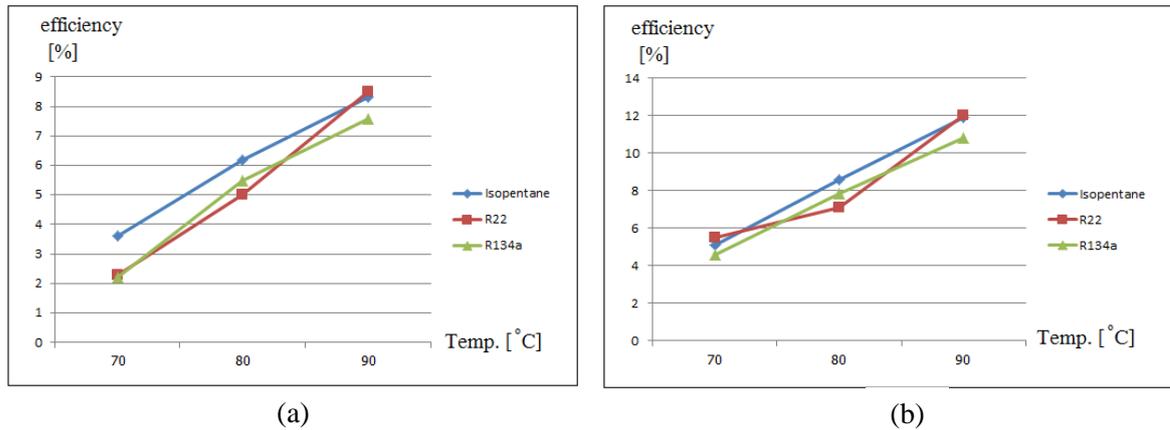
6. Major Findings

The result of the experiment and calculation of ORC using Isopentane efficiency was 30% better than R22 and R134a estimate. The result of the experiment and calculation of ORC Machine using centrifugal Turbine efficiency was better than Tesla turbine at 28%. As known, the Tesla Turbine is cheaper and easily structured than other turbines which can be applied on Organic Rankine Cycle Machine.

The study reveals that low-temperature sources have low power outputs. If we use low-temperature sources from various natural and renewable sources, such as geothermal energy, waste heat, and solar-thermal energy, we tend to have working fluids with the efficiency of work.

7. Conclusion

The experiment on ORC using Tesla turbine and Centrifugal Turbine reveals that the suitability of high pressure pump for working fluid has good results on the efficiency of work. The thermodynamics theory on P-h diagram also presents the effect of heat sources' temperature and flow rate on any work.

The result of the experiment and calculation of ORC Machine using centrifugal Turbine efficiency was better than Tesla turbine at 28%. As known, the Tesla turbine is cheaper and easily structured than other turbines which can be applied on Organic Rankine Cycle Machine. Suitable low-temperature sources from various natural and renewable sources such as geothermal energy, waste heat, and solar-thermal energy can yield efficiency in optimized temperature. Further studies could be pursued for lower cost and greater efficiency.

8. The Author

Kosart Thawichsri is an Assistant Professor in Energy and Environment, the Faculty of Engineering and Technology, Siam Technology College, Bangkok, Thailand. He has a keen research interest in the areas of automotive technology, particularly in different working fluids, and applications of turbines in Organic Rankine Cycle.

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