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ANALYSIS OF A LOW-GRADE HEAT DRIVEN TRILATERAL CYCLE WITH SINGLE-STAGE IMPULSE TURBINE

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Abstract — Trilateral cycle (TLC) is preferred for low-grade heat recovery due to the absence of pinch limitation. In the present study performance of a trilateral cycle is evaluated using R245fa, R1234ze (Z) and R1233zd (E) as working fluids. A single-stage impulse turbine is considered as the turbomachine of the cycle. During the analysis, instead of considering fixed isentropic efficiency of the turbine, velocity triangles are considered for the estimation of the turbine power output. The study indicates that the TLC operating with R1234ze (Z) as well as R1233zd (E) yields power output which is comparable to that of the TLC using R245fa. Thus, for the TLC, R1234ze (Z) or R1233zd (E) may be used as the possible drop-in replacement of R245fa.

Keywords – Trilateral cycle; Impulse turbine, R245fa

1. INTRODUCTION

IEA reported that global demand for electricity increased by 4% in the year 2018[1]. Growth of renewable technologies is also not fast enough to eliminate fossil fuel-based power plants. It is important to note that a significant part of primary energy input to industries is wasted and released to the ambient as low-grade heat. This low-grade waste heat may be used to produce electricity if suitable conversion technologies are available. Organic Rankine cycle [2-4], Organic flash cycle [5-7], transcritical CO_2 power cycles [8-10] are some of the possible technologies that can be used to produce the secondary energy from low-grade heat. Due to the absence of pinch limitation, a trilateral cycle is preferred to recover low grade waste heat of the industrial flue gas free from SO_2. Iqbal et al. [10] showed that power output potential of a TLC was appreciable higher compared to that of a conventional organic Rankine cycle. Smith et al. [12] concluded that a TLC would be more advantageous compared to an ORC if isentropic efficiency of the two phase expender is more than 75%. Fisher [13] evaluated performance of a TFC using water as the working fluid. Marchionni et al. [14] conducted off-design analysis of a trilateral flash cycle using the twin screw expander as the turbo-machine. Through a simulation, Ajimotokan and Sher [15] evaluated performance of a TFC using nonconventional working fluids.
In present study performance of a TLC is analysed using R245fa, R1234ze (Z) and R1233zd

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(E) as working fluids. R245fa is considered as the working fluid due to its zero ozone

depletion potential and non-inert characteristics. However, GWP of R245fa is close to thousand. On the other hand GWP values of remaining two working fluids are less than ten and they are mildly flammable. Thus, if TFC exhibits satisfactory performance with R1234ze (Z) and R1233zd (E), these Woking fluids can be considered as alternative working fluids of R245fa. A single stage impulse turbine is considered as the turbo machine of the present study. Thus, turbine power output is estimated from the velocity triangle of the considered single stage impulse turbine.

2.SYSTEM LAYOUT

The T-s diagram of a trilateral cycle is presented in Fig. 1. Working fluid after being heated to saturated liquid state (i.e. state-1) is accelerated in a nozzle. Nozzle exit pressure is same as that of the condenser as pressure drop in impulse turbine is assumed to be negligible.

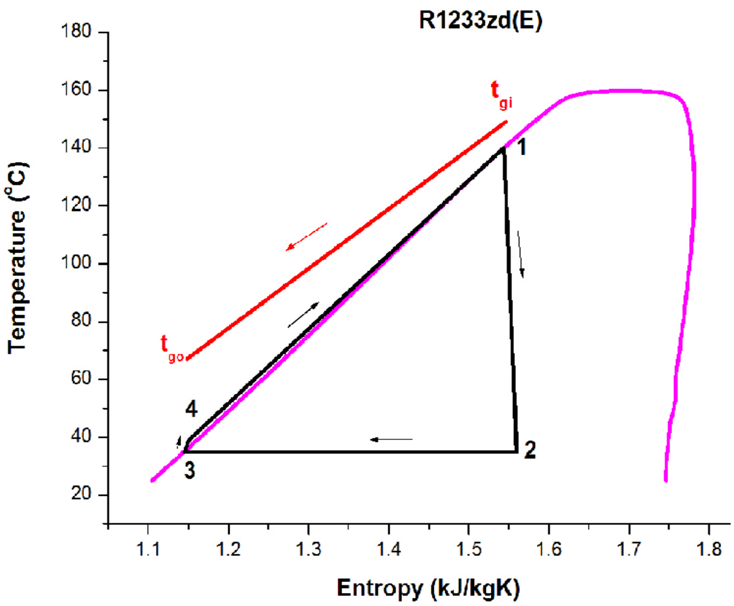

Fig. 1 T-S Diagram of TFC

Working fluid exiting the nozzle after being expanded in the single stage impulse turbine enters into the condenser (i.e. state-2). In this study instead of compounded impulse turbine single stage impulse balding is considered as velocity of working fluid exiting the nozzle is not appreciably high. The working fluid exiting the condenser (at state-3) is pressurized to the heat recovery unit pressure (i.e. state-4) by using a pump

3. MATHEMATICAL MODELLING

Mass flow rate of working fluid is estimated from the energy balance of the heat recovery unit (HRU) as follows

$$\dot{m}_f = \frac{\dot{m}_g c_{pg}(t_{gi} - t_{go})}{(h_1 - h_4)} \qquad (1)$$

In above equation $\dot{m}_g$ is the mass flow rate of flue gas. t_{gi} and t_{go} are representing HRU inlet and exit temperature of flue gas.
The cycle power can be estimated by using the eqn-2.

$$\dot{W}_{Cycle} = \dot{W}_{Turbine} - \dot{W}_{Pump} \qquad (2)$$

The pumping power output is estimated by using the following equation

$$\dot{W}_{Pump} = \dot{m}_f\ (h_4 - h_3) \qquad (3)$$

The turbine power output is estimated with the help of the following velocity triangle.

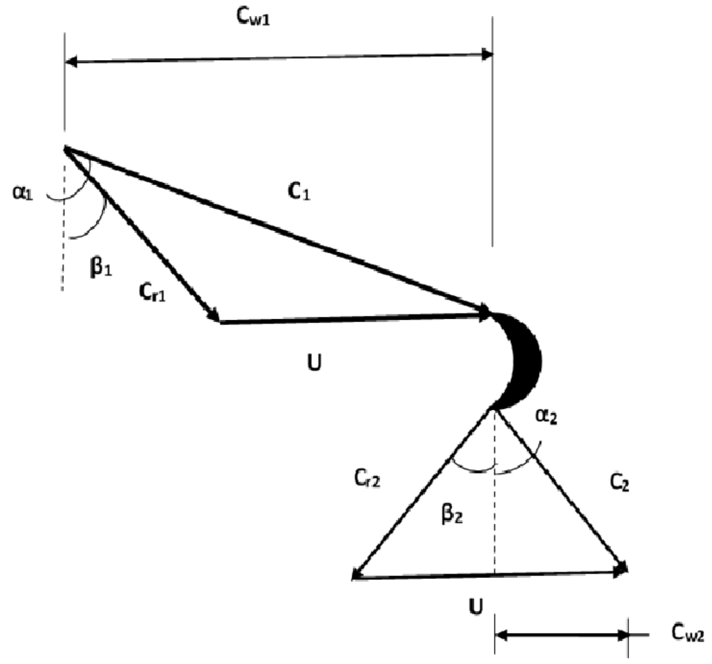

Fig. 2 Inlet and exit velocity triangle for the single stage velocity triangle

The inlet velocity of working fluid (or nozzle exit velocity) to the turbine can be estimated as

$$C_1 = \sqrt{2000\eta_N(h_1 - h_{2s})} \qquad (4)$$

While calculating this velocity, pressure drop in turbine is neglected due to the impulse balding.

With the help of inlet and exit velocity triangles turbine power output can be evaluated as follows:

$$\dot{W}_{Turbine} = \dot{m}_f U \, (C_{W1} - C_{W2}) \qquad (5)$$

While estimating turbine power output, frictional loss coefficient of turbine is assumed to be 80%. Axial components of inlet and exit velocity triangles are assumed to be equal to make axial thrust on turbine zero.

4. RESULTS AND DISCUSSION

In this study first velocity ratio of the turbine is optimized to obtain the maximum turbine power output for each of the specified operating conditions. While optimizing the velocity ratio nozzle angle (α) is assumed to be 70°.

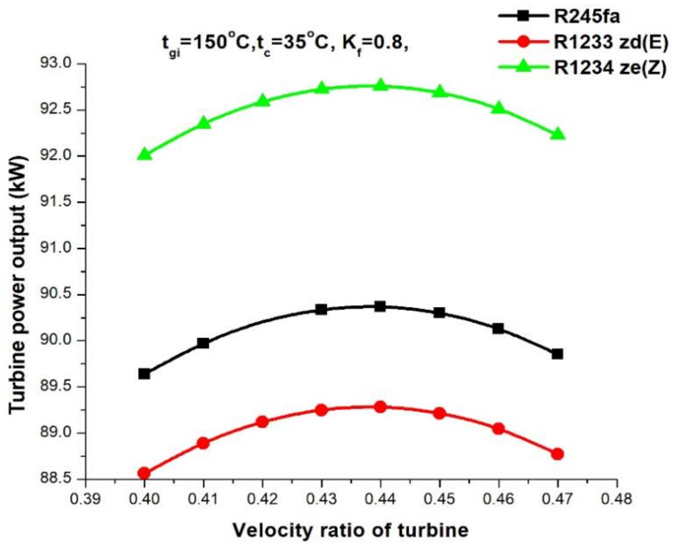

Fig. 3 Turbine power output vs. Velocity ratio of turbine

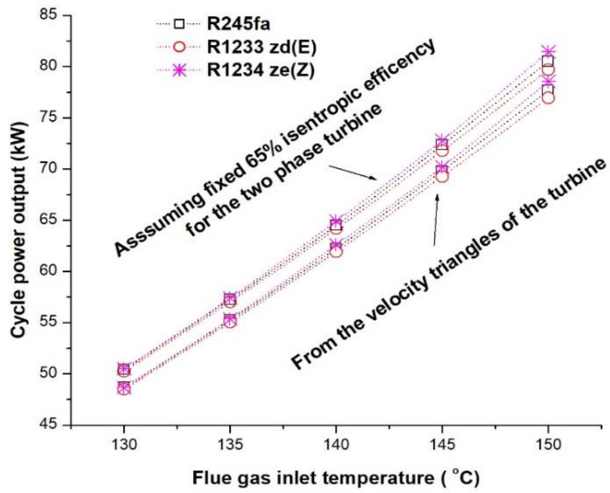

Fig. 4 Net cycle power output vs. Flue gas inlet temperature

In Fig.3 turbine power output is plotted against the turbine velocity ratio for three considered working fluids in Fig.3. It is observed that maximum possible turbine power output with R1234ze (Z) is appreciably higher compared to that of with remaining two working fluids. Turbine power output is appeared to be lowest for the cycle operating with R1233zd (E).

Effect of varying flue gas inlet temperature on net cycle power output is presented in Fig.4. During the analysis terminal temperature differe nces at low and high temperature ends of the HRU are assumed to be 10^{o}C and 30^{o}C respectively.

It is clear from Fig.4 that for entire range of considered flue gas inlet temperature, TLC yield almost equal cycle power output with each of the considered working fluids. This is occurring because pumping power output is appeared to be higher for those working fluids that yield higher turbine power output. It is further observed that cycle power output with 65% isentropic efficiency of two-phase turbine is slightly higher compared to the estimated cycle power output from the velocity diagrams.

5. CONCLUSION

In present study performance of a low grade heat driven tri lateral cycle (TLC) is evaluated using R245fa, R1234ze (Z) and R1233zd (E) as working fluids. A single stage impulse turbine is considered for producing the cycle power output. The result indicates that if analysis is conducted assuming 65% isentropic efficiency of the two phase turbine power output is appeared to be somehow higher compared that of estimated from velocity diagrams of the turbine. Both methods indicate that power outputs with R1234ze (Z) and R1233zd (E) are almost equal to the power output obtained with R245fa. As global worming potentials of R1234ze (Z) and R1233zd (E) are less than 10, these working fluids may be considered as the future drop-in replacement of R245fa.

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