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Analytical method for calculation of heat source temperature drop for the Organic Rankine Cycle application

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HIGHLIGHTS

- Considered is variable temperature heat supply to ORC.
- Single phase and phase changing fluids considered as heat supply.
- Possibility of analytical determination of outlet temperature of heat supplying fluid for both considered cases.

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ABSTRACT

In the paper presented are considerations on the cooperation of the limited capacity heat source with the Organic Rankine Cycle unit. Usually the heat source providing thermal energy to the Organic Rankine Cycle (ORC) may have twofold characteristics. It can be in the form of a single phase fluid, i.e. as hot exhaust gas or hot liquid, or in some cases it may be available as a phase changing fluid, as for example, technological or geothermal steam. Such fluid will be condensed whilst supplying heat to the ORC evaporator. In case of the heat source in the form of a single phase fluid flow its temperature is decreasing in the course of heating of the ORC. In the paper a simple analytical method, based on the energy balance of evaporator, is presented for evaluation of the final temperature of the heat source for ORC installation for two cases, namely single phase fluid and phase changing fluid heat supply. Additionally, the ratio of the heating fluid to the ORC working fluid is presented in function of the minimum temperature difference between the heat source and working fluid.

1. Introduction

Considerable quantities of low-temperature thermal energy are available from natural sources (solar, geothermal, biomass) and industrial processes in the form of waste heat (power plants, chemical plants, etc.). Conversion of such energy into mechanical energy and subsequently to electricity is considered nowadays as a challenge and presents great opportunities. One of the branches of methods which can be used to achieve such conversion include implementation of the vapor Clausius–Rankine cycle with organic substance as the working fluid, the so-called Organic Rankine Cycle (ORC).

Plant should be operated to achieve the highest conversion efficiency from the available heat source. Therefore, an optimal combination of evaporation temperature and mass flow rate of working fluid must be sought. The heat source providing thermal energy to the Organic Rankine Cycle is available usually in the form of hot exhaust gas or hot liquid flow. In some cases we may have at our disposal a phase changing fluid, which comes for example from the technological or geothermal vapor, which is condensing whilst supplying heat to the ORC evaporator. The characteristic feature of the single phase fluid heat source is that its temperature decreases when heat is extracted. That is also true in case of the condensing fluid, but in that case the distribution of temperature is different. In the case where there is a small temperature difference between the heat source and the ORC working fluid there can arise some kind of difficulty in heating and evaporating of the working fluid. During such process, the requirement for the existence of the minimum temperature difference between heating fluid and working fluid, the so-called “pinch temperature” restricts the reduction of the available heat source temperature to the demanded level,

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contributing to the ineffective use of such heat source. That minimum temperature difference between the two media is usually assumed as 5 °C. The attempt to utilize the heat source to the full extent, revealed in the significant reduction of its temperature, leads usually to lower evaporation temperatures of the working fluid in the ORC system, thus contributing a substantial reduction of thermal efficiency of ORC [1]. The evaporation temperature of working fluid is regarded as one of the major parameters influencing the ORC efficiency. Majority of contributions in literature for ORC analyses treat the heat source as if it had an infinite heat capacity, that is its temperature remains constant (or vary to a small extent) during the heat supply to ORC. It leads to the fact that the heat source is not well exploited and in the case of waste heat utilization it can prove the poor economics of the ORC. Additionally, in order to sustain a small temperature drop of the heat source, the mass flow rate of heating fluid must be large, leading in such way to large pumping power.

Liu et al. [2] analyzed the effect of working fluids (water, ethanol, HFE7100, *n*-pentane, iso-pentane and isentropic: R11, R123, benzene) on the performance of subcritical ORCs. They indicated that assuming a constant heat source temperature can result in considerable design differences with respect to the actual variable temperature of finite heat sources such as geothermal or waste streams. Additionally they reported that the thermal efficiency of such cycles is a weak function of the critical temperature.

Saleh et al. [3] performed a thermodynamic analysis of 31 pure working fluids for ORCs with and without superheating, operating in temperature range between 100 °C and 30 °C. They found that the highest thermal efficiencies are obtained with dry fluids in subcritical cycles with regenerator. They also performed the “pinch analysis” for the heat transfer between the source and the working fluid, and reported that the largest amount of heat can be transferred to a supercritical fluid and the least to a high-boiling subcritical fluid.

Lakew and Bolland [4] analyzed the power production capability and equipment size requirements for R134a, R123, R227ea, R245fa, R290 and *n*-pentane. They used a subcritical Rankine cycle without superheating, specified the heat source temperature in the temperature range from 80 °C to 200 °C and used the evaporator pressure as independent parameter. Their results show that the selection of working fluids depends on the type of heat source, the temperature level and the design objective. The latter can be either the maximum power output (turbine) or the smaller heat exchangers. It was shown that the maximum power is obtained for the optimal evaporator pressure. Furthermore, a working fluid may have the smallest turbine size factor but requires a large heat exchanger area. The authors concluded that an economic study is necessary to determine which working fluid is the most appropriate.

Recently Khennich and Galanis [5] compared the performance of a subcritical Rankine cycle with superheating, operating between a constant flow rate fixed-temperature (100 °C) heat source and a fixed-temperature (10 °C) sink, for five working fluids. Their results show the existence of two optimum evaporation temperatures. One minimizes the total thermal conductance of the two heat exchangers whereas the other maximizes the net power output.

There are numerous other works where fitting of the heat source to working fluid is considered to find optimum operation conditions of the ORC plant. The present work, however, is not about finding optimum operation conditions of ORC, but the relation between temperature drop of the heat source and possible evaporation temperature at a given minimum temperature difference between two fluids. Having obtained the initial and final temperatures of the heat source, evaporation temperature and the ratio of mass flow rates of heating fluid to working fluid one can embark on the search of adjusting these conditions using other criteria. One of them to mention is to seek the ratio of the total heat transfer area to the total net power, Hettiarachchi et al. [6]. In literature, however, the usual approach to configure the heat source to the ORC is such that the exergy losses are sought to be smallest. Such approach can be found in Quoilin et al. [7], who developed a map of cycle efficiency on the basis of combination of mass flow rate/rotational speed. Astolfi et al. [8] presented numerous heat exchanger profiles on a temperature–heat plane explicitly expressing the need to a correct match of the heat source and working fluid heating characteristics. Tchanche et al. [9] indicate that the heat amounts transferred to the cycle through the preheater and evaporator depend upon the fluid. Therefore, the pinch point analysis should be considered when designing the system for an efficient heat transfer in the preheater and evaporator. Zhou et al. [10] uses exergetic efficiency along with cycle efficiency, heat recovery efficiency and output power of expander to evaluate the system performance. El-Emam and Dincer [11] introduced a sustainability index which is defined as a function of exergy efficiency and claim that exergy analysis appears to be a significant tool for energy systems which may contribute in improving the sustainable development.

In the present study cooperation of the ORC with the heat source available as a single phase or phase changing fluids is considered. The analytical models have been developed, which enable in a simple way calculation of heating fluid temperature variation as well as the ratio of flow rates of heating and working fluids in ORC. The developed analytical expressions enable also calculation of the outlet temperature of the heating fluid. These relations, however simple, have not been found in literature of the subject. That is may be due to fact that normally the heat source temperature drop was not considered as crucial. In case of utilization of low-enthalpy heat, such as waste heat or geothermal heat, when there is an issue of highest possible utilization of the heat source, the possibility of straightforward determination of final temperature of the source may be important.

2. Analytical model for calculation of heat source temperature drop in ORC installation

The simple Organic Rankine Cycle is considered, consisting namely of the evaporator, turbine, condenser and circulation pump, Fig. 1. In case of so-called “dry” fluid, i.e. a fluid featuring a positive slope of the vapor saturation line in temperature–entropy diagram, the internal regeneration of the ORC could also be considered, Fig. 2. In the analysis it is assumed that the working fluid is in the state of saturated liquid at the outlet of the condenser. Its pressure

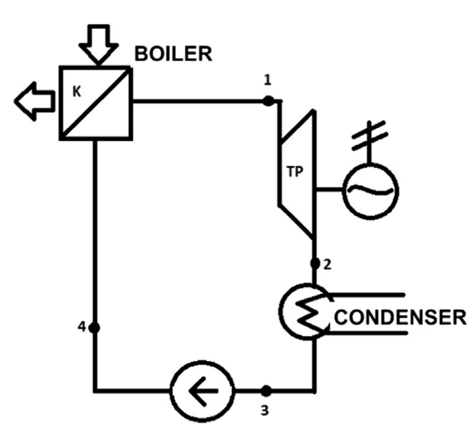

Fig. 1. Scheme of the wet ORC without regeneration.