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THERMODYNAMIC ASSESSMENT OF LIQUID METAL–STEAM USC BINARY PLANTS TO BREAK 50% EFFICIENCY IN PULVERIZED COAL PLANTS

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Abstract

Nowadays the state-of-the-art technology to convert coal energy of combustion into electricity is to adopt a pulverized coal boiler coupled with an Ultra Super Critical (USC) steam cycle. The total installed capacity of this well-proven configuration is of hundreds of GW worldwide with an increasing share respect to both supercritical and subcritical cycles. Typical coal USC cycles have maximum pressures of around 270 bar and maximum temperatures of 600-620°C for the high pressure and the mid pressure steam respectively. Maximum attainable efficiency is close to 45% in favorable locations and is mainly penalized by two irreversible processes: coal combustion (about 30%) and heat introduction (about 10%) that is characterized by large temperature differences between the hot flue gases and the steam. The main strategy to reduce the second loss is focused on the development of new super alloys able to withstand higher temperatures, higher pressures and water corrosion and so bring efficiencies close to 49% in the so called Advanced USC plants (AUSC). However, the increasing of maximum cycle pressure and temperature results in a relatively small increase of cycle efficiency due to the large increase of specific heat around the critical point but, on the other hand, it involves a considerably increase of equipment's cost. Another option to increase cycle efficiency is represented by the introduction of a high temperature and low pressure power cycle between the flue gases and the steam cycle. In this case, the topping power cycle could be (i) an external combustion gas cycle, (ii) an open gas cycle fueled by syngas produced by coal gasification or (iii) a Rankine cycle that uses a proper working fluid with a very high critical temperature. This study aims to define a number of optimized binary plant configurations with saturated Rankine potassium cycle as top cycle and a conventional USC plant as bottom cycle. Top cycle receives heat from the flue gases within the coal-fired boiler while bottom cycle recovers heat from the top cycle fluid condensation and the flue gases cooling before the Ljunström air preheater. Potassium thermodynamic properties are computed with a proper equation of state calibrated on experimental data from reference [2] and able to predict accurately both the volumetric and the thermodynamic behavior of potassium in liquid, vapor and two-phase conditions. Different liquid metal cycles have been designed and the trends of the main quantities (heat of condensation, turbine isentropic enthalpy drop and plant efficiency) have been correlated to both evaporation and condensation temperatures. This information is implemented in the USC scheme, calculated with an in-house process simulation code GS developed at the Department of Energy at Politecnico di Milano [3], which has been validated and used on hundreds of publications and projects. Analysis is completed by the evaluation of the potassium turbine design in terms of number of stages, need of cross-over and optimal rotational speed. A double condensation level configuration is also considered for the top cycle in order to further reduce the temperature difference between the top cycle condensation and evaporation process in the bottom cycle, which further increases the efficiency. The thermal input of coal to the burner is fixed for all the simulations to 1.66 GW, five plant configurations have been selected as the most promising ones and fairly compared with a conventional USC coal-fired power plant having a calculated efficiency equal to 44.72%. Limiting the maximum potassium temperature at 800°C, which corresponds to an evaporation pressure of 1.5 bar, it is possible to reach electric efficiencies close to 51% with a single condensation level top cycle and value close to 52% with a double condensation level top cycle. Power produced by the metal cycle ranges between 25 and 30% of the net system power output. As general conclusion

the adoption of binary cycles with a top Rankine liquid metal cycle is demonstrated to be an attractive option from a thermodynamic point of view leading to an electric efficiency larger than in AUSC plants. However, these binary metal-steam cycles still need to face a number of technical and safety issues mainly related to the use of liquid metals. Technical issues are related to the high temperature of heat exchange surface of the boiler, to the very high vacuum at condenser, the need of limiting air leakages and the design of a turbine expanding a fluid with an increasing liquid fraction. Safety issues are due to working fluid reactivity with water that requires the need of expensive solution to limit fire hazard.

[1] World Energy Council, 2016. World Energy Resources: Coal.
[2] Reynolds, W.C. Thermodynamic properties in SI - graphs, tables and computational equations for 40 substances. Department of Mechanical Engineering, Stanford Univ., 1979
[3] GECOS, GS software. www.gecos.polimi.it/software/gs.php