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Dynamic simulation of a small modified Joule cycle reciprocating Ericsson engine for micro-cogeneration systems

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ABSTRACT

The Ericsson engine is an external combustion engine suitable for the use of certain energy sources such as solar energy, biomass and waste gases at high temperature, and thus contributes to the fight against global warming. Its open cycle configuration considered in this study can achieve good performance in low power range, most particularly in micro-cogeneration applications. The dynamic model of this engine which is the purpose of this study, takes into account both the pressure losses and the variation of the thermophysical properties of the working fluid as a function of the temperature in the system. The coded models are implemented on a Matlab/Simulink platform where the start-up dynamics and performance simulations are conducted. The optimal settings of the expansion cylinder valves, as well as the characteristic parameters of the engine are thus determined. In this configuration the engine develops a power output of 1.72 kW and reacts well when subjected to a selected perturbation.

1. Introduction

Oil is a non-renewable source of energy whose price per barrel is continuously increasing with changes in economic and market conditions. This situation on the one hand forces motorists to adopt new spending habits and on the other hand contributes to the rise in social and political tensions worldwide. One of the challenges in the field of the thermodynamic conversion of energy consists in designing engines that are efficient, environmentally friendly and capable of using various renewable energy sources.

This is the reason why many studies are carried out in the research and scientific fields as well as in industries. In the field of dish/Stirling solar systems, the Sandia National Laboratories and Stirling Energy Systems [1] obtained an electric efficiency record of 31.25% in 2008 with a concentrated solar energy Stirling plant producing 26.75 kW in New Mexico (United-States). The gas turbine also ranks among the engines that can potentially be used to develop thermal sources of renewable energy. For CHP (combined heat and power) purposes, gas turbines generally produce electricity ranging from 1 MW to 30 MW; micro-turbines on the other hand cover the power level up to 30 kW. A study [2] on the impact of the sizing to the performances of a micro-turbine with heat recovery suggests that the efficiency of this kind of engine is strongly deteriorated at low power range: it is estimated at 22.5% for a 5 kW installation, whereas it would have been about 27% for a typical 30 kW engine. The development of such micro-turbines (1–5 kW) being able to meet the needs of domestic CHP for example, seems to be difficult (leakage, low efficiency, cost, etc.). In this power range, the reciprocating internal combustion engine operation is expensive (especially maintenance) and noisy. The Joule cycle reciprocating Ericsson engine seems more suitable for thermal energy conversion in the low power range [3,4].

According to existing literature, some studies have reported theoretical developments on Joule cycle reciprocating engines, both on aspects of thermodynamic optimization and performance study in view of their implementation in the cogeneration sector. Indeed, Senft [5] got interested in the mechanical performances of reciprocating thermal engines by developing general mathematical models. He came out with the conclusion that among all the reciprocating engines, the ideal Stirling cycle has the maximum mechanical efficiency. Bell and Partridge [4] conducted a study

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under steady-flow conditions on an open Joule cycle reciprocating engine with regeneration, which was intended to be implemented in the cogeneration system and decentralized energy production. In a study conducted by Moss et al. [6] on a Joule cycle reciprocating engine similar to the one described above and designed for domestic micro-CHP, the problem of dimensioning was examined. The study predicts a thermal efficiency of 35% and an overall electrical efficiency of 33.2%. However, this level of performance is dependent on the relatively high values of the pressure ratio (equal to 7.5) and the engine rotational speed (1000 rpm). Wojewoda and Kazimierski [7] performed a dynamic model to describe operating conditions of an externally heated reciprocating valve engine, based on the closed Joule cycle with highly pressurized air of 25 kW, which could reach a thermal efficiency of up to 25%. However, in order to achieve this level of performance, the system requires a high rotational speed (3000 rpm) and a relatively high compression ratio (compressed air from 15 to 95 bar). It is noted that the heat transfer takes place at over 1160 K in the heater, making it difficult to achieve such an air heat exchanger for this engine. In this study, the transient problems related to the start-up and the driving of this type of engine were however not examined. More recently, Creyx et al. [8] developed a steady state model of the Ericsson engine based on modified Joule cycle which allows a thermodynamic optimization of the engine performances. Considering the modification of the thermodynamic compression and expansion cycles (isothermal and isentropic transformation) the model simulation predicts that the Joule cycle is more adapted to enhance the engine performances than the Ericsson cycle, while the adjustments of the Joule cycle (late inlet valve closing and early exhaust valve closing in the expansion cylinder) lead to the conclusion that heat transfers in the expansion cylinder wall should be enhanced for an optimized indicated mean pressure and an optimized specific indicated work, or should be avoided to improve the thermodynamic efficiency. Despite the results obtained in this study, it should however be noted that the simulated steady state model does not take into account the frictional effects, the pressure drops across the valves and in the heater.

As for all energy systems the understanding and the control of the dynamic behavior of Joule cycle reciprocating Ericsson engines are an important aspect of the development of this kind of machines [9]. In fact, it is necessary to be able to manage the transient phases (such as star-up and part load), and to guarantee the stability of operation around the nominal operating point. The objective of this work is to develop a tool for the modeling and the dynamic simulation of reciprocating Joule cycle engines which makes it possible to anticipate the possible problems of operation stability that could occur, in order to set up devices and strategies of control for such systems.

The engine configuration under study will be presented and its dynamic model developed subsequently. Before concluding this work, all the results obtained from simulations are presented and analyzed.

2. The Ericsson engine

2.1. Principle and reference cycle

A classification of heat engines has been proposed in a former study [10]. It made it possible to identify a family of specific machines: reciprocating engines with external heat supply, with separate compression and expansion cylinders, with or without regenerator, with gaseous working fluid. This family of engines includes two sub-families; the Stirling engines, working without any kind of valves (Fig. 1) and the Ericsson engines (Fig. 2) using valves at the inlet and outlet of the cylinders.

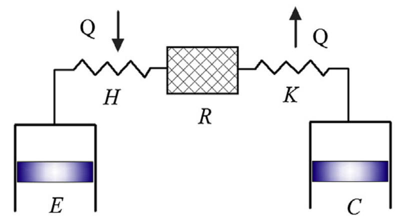

Fig. 1. Typical Stirling engine.

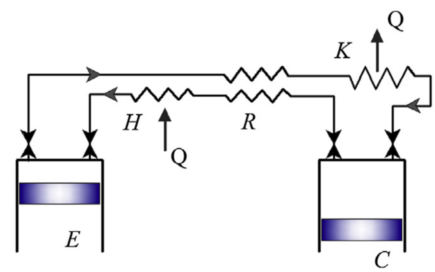

Fig. 2. Typical Ericsson engine.

From the thermodynamic point of view, the Ericsson engine is similar to a gas turbine engine where the turbo-compressor has been replaced by a reciprocating compressor and the turbine by a piston/cylinder machine. The theoretical cycle of Ericsson (2 isotherms and 2 isobars) is not adapted to describe an ideal Ericsson engine [11]. In an ideal Ericsson engine, heat transfers should take place at constant pressure while compression and expansion are supposed to be isentropic, corresponding to the Joule cycle, often used to describe the gas turbine engine principle.

2.2. Description of the studied Ericsson engine

The Ericsson engine can be operated either by a closed cycle (Fig. 2) with cooler K (in this case the system can run at high pressure and allows the use of working fluids such as helium or hydrogen), or by an open cycle with or without regeneration R. In this case, the working fluid is air that can be expanded down to the atmospheric pressure. For this study, an open Joule cycle without heat recovery, with a modified compression cycle is considered (Fig. 3). The open cycle was identified to correspond to present needs in the field of domestic micro-CHP, as well as for solar or wood-energy conversion of energy into electricity [3,12]. In these engines, the compressor and the expansion cylinder run at a low rotational speed, in order to limit pressure losses caused by valves as well as to reduce the mechanical losses. This solution ensures the best performance.

The atmospheric air is compressed by the compressor C. It receives heat Q from the thermal source through the heater H. The pressurized hot air produces work by expansion in the expansion cylinder E. The expander cylinder is externally insulated and

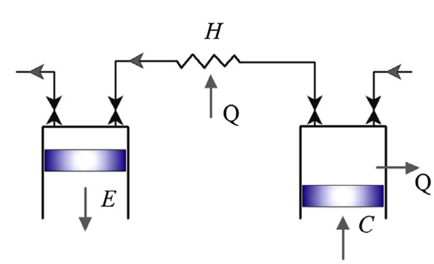

Fig. 3. Open cycle Ericsson engine without heat recovery.