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Experimental and simulation studies of steady- and transient-state operation of thermoelectric systems for cooling and electricity generation

PhD Thesis

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Scientific discipline:

Environmental Engineering, Mining and Energy

Gliwice, 2022

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Polish title:

Eksperymentalne i symulacyjne badania pracy układów termoelektrycznych w układach pompy ciepła oraz generatora elektryczności w stanach ustalonych i nieustalonych

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ABSTRACT

The dissertation addresses the issue of simulating the operation of systems equipped with thermoelectric modules. A distinctive quality of the research was consideration of the thermal resistance occurring between the thermoelectric junction and the heat exchanger. The theoretical basics of thermoelectric phenomena are shown and their characteristic features and mutual implications are discussed. The dissertation also presents their possible applications. The structure of the thermoelectric module is discussed, and the effect of the module geometric and material characteristics is described. Example simulations are presented of thermoelectric modules operating both as heat pumps and as electricity generators using the applied temperature gradient and the resulting heat flow.

A method was developed of determining parameters of the thermoelectric module and thermal resistance in the system using transient-state measurements that make use of the significant differences in the inertia of the thermal and the electric field. The developed methodology makes it possible to find the theoretical maxima of the system operating parameters and answers the question about the reasonableness of actions aiming to improve thermal contact in the system. The degradation of this contact can also be assessed over time. Also presented is the constructed test stand, which enables comprehensive evaluation of thermoelectric modules in any operating states and in a very wide range of parameters. The stand is fully automated, abundantly metered and computer-controlled using controllers.

In order to perform numerical simulations of the operation of systems using thermoelectric modules, multifunctional software based on developed analytical models was prepared. The software enables simulations of transient-state operation of one- and multi-stage systems. It is fitted out with procedures for designing and analysing the system geometrical features, as well as optimizing its operating conditions. The software was used to perform a number of numerical simulations of thermoelectric systems operating in the mode of both an electricity generator and a heat pump. The software was also validated experimentally on the aforementioned test stand.

First, the operation of the thermoelectric generator system was analysed for a wide range of contact thermal resistances. The effect of the resistance magnitude on the thermoelectric junction temperatures, maximum power and maximum efficiency was determined, and the optimal values of the electric current in terms of the maximization of the module power or efficiency were established.

The next step was to simulate the system of a two-stage thermoelectric cooler. The cooler operating characteristics and the ability to reach temperatures lower than those achievable in the steady state – the supercooling effect – were investigated. The system was optimized in terms of the selection of the number of thermoelectric legs for each stage to ensure temperature minimization and in terms of electric current shaping. The calculations were carried out for two different values of contact thermal resistance, and the performance of the optimized one- and two-stage system was compared.

Next, a concept of a thermoelectric air conditioner built using commercially available modules was presented. The parameters of the modules were determined independently on the

constructed test stand, and the results of the performed numerical simulations were validated experimentally. Economic analyses were also conducted of the proposed system, taking account of investment costs in the form of the purchase of modules and heat exchangers, along with the operating cost related to the consumption of electricity over the assumed lifetime of the device. The simulations in this regard were carried out with a varying number of thermoelectric modules, various dimensions of the heat exchangers and different values of the power supply so that the maximum cooling efficiency factor could be obtained. The efficiency related to the total cost was evaluated using the introduced $ETCC$ indicator. The calculations were performed in a wide range of electricity costs and a set difference between the outdoor temperature and the temperature of the air-conditioned room. Moreover, independent calculations were made assuming the possibility of modifying the geometry of the module internal elements. The possibility of increasing the cooling power at the expense of a reduction in the value of the economic cooling efficiency factor was investigated.

A thermoelectric device for waste heat recovery by means of electricity generation was simulated for a system installed at the exhaust of an internal combustion engine. The calculations were carried out using a specialist AVL BOOST software intended for modelling the operation of internal combustion engines, in which an own module analysing the operation of the thermoelectric heat recovery system was implemented. These tests were carried out for a motorcycle engine, where it was checked how the number of the proposed heat recovery segments affected the amount of the produced electricity depending on the internal combustion engine operating parameters. Next, calculations were performed for a passenger car engine during simulated driving cycles. The calculations took account of the thermal capacity of the heat exchanger placed between the thermoelectric modules and the flowing exhaust gas. Tests were performed to establish the impact of the heat exchanger thermal capacity on the amount of recovered energy, and the capacity optimal value was determined for assumed criteria.