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Design and optimization of a natural gas-fired thermoelectric generator by computational fluid dynamics modeling

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ABSTRACT

The paper reports the results of the computational part of an ongoing research and development project aimed at designing and optimization of a thermoelectric generator fired with natural gas. The idea of the project is to provide an independent and reliable source of power in the power range of 50–100 W for island-mode supply, tailored for remote objects of the natural gas distribution infrastructure which, for economic reason, are not connected to the electric grid. The device includes a burner as a heat source, flow channels for air and for exhaust gases and a set of thermoelectric modules generating electric current if subject to temperature difference. The pre-selected design configuration (type E) was subject to parametric optimization. A corresponding numerical model based on the Ansys/Fluent computational fluid dynamics code was built. The optimization procedure aims to maximize the temperature difference across the thermoelectric module in order to maximize the generated power output. Simultaneously, it is essential to maintain the hot-side temperature below the required technical limit of 320 °C. First, thirteen design parameters (most of them concerning geometry) influencing the target function were identified. A central value and a possible range for each parameter have been set. Next, the partial impact of each parameter on the target function was found, and the set of the design parameters was limited to eight. Finally, only five parameters were estimated to be non-monotonically related to the generated power. The impact of the selected five parameters on the target function was investigated using a central composite design optimization plan. The set of points obtained in the multi-dimensional response surface was then limited to points meeting the imposed limitation of maximum temperature. Eventually, three candidate points (i.e. three sets of design parameters) have been proposed for the next stage of the project involving an experimental set-up for the design of the prototype.

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1. Introduction

Natural gas remains one of the key energy sources for the World, covering 23.8% of the primary energy consumption in 2015 [1]. Transportation of this fuel from gas wells to consumers requires an extensive infrastructure, organized in the sectors of high-pressure, long-distance *transmission*, medium/low-pressure, short-distance *distribution* and supplemented with the sectors of gas storage and LNG. In Europe (EU-28), the transmission sector comprises about 200,000 km of pipelines [2], and the length of distribution networks can be estimated as by one order of magnitude higher [3]. The distribution networks are operated under intermediate, medium and low pressure levels. Sections of network under different pressure are connected via pressure letdown stations (PLS). The number of PLS's installed worldwide or at the EU level is not reported, in Poland this number exceeds 3500 objects per 170,000 km of distribution pipelines, i.e. approximately 1 object per 50 km of network.

A PLS typically combines the functions of 1: pressure reduction, 2: demand-supply management through flow regulation and 3: flow metering. For the network operator, it is essential to remotely supervise all PLS objects in order to react if some parameters (pressure/flow rate) indicate a failure in the system. Nowadays, particular attention is paid to reduce the negative environmental impact of natural gas along the paths of transmission and distribution. It is essential to minimize the quantity of uncombusted methane released to the atmosphere during failures and maintenance works due to its global warming potential exceeding the value of 25. The negative impact of this emission was quantified by Stanek and Białecki [4], who conclude that the level of 4% losses

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Nomenclature

A_b	cross section area of the burner zone, m^2
e	specific energy of fluid, J/kg
$\mathbf{g}$	gravitational acceleration vector, m/s^2
h_j	specific sensible enthalpy of species j, J/kg
$\mathbf{J_i}$	diffusion flux of species i, $kg/(s \cdot m^2)$
k_e	effective heat conductivity, W/(m·K)
$\mathbf{u}$	velocity vector, m/s
p	pressure, Pa
$\dot{Q}_b$	power of the burner, W
S_{en}	energy source, W/m^3
S_i	mass source of species i, $kg/(s \cdot m^3)$
S_m	mass source, $kg/(s \cdot m^3)$
$\mathbf{S_{mom}}$	momentum source vector, $kg/(m^2 s^2)$
Sc_t	turbulent Schmidt number
ϑ	temperature, °C
T	absolute temperature, K
$\overline{\vartheta}_{cold,\ TE}$	mean cold side temperature of the TE, °C
$\overline{\vartheta}_{hot,\ TE}$	mean hot side temperature of the TE, °C
$\vartheta_{hot,TE}^{max}$	maximum hot side temperature of the TE, °C
$\Delta\overline{T}$	difference of mean temperatures, the objective function, K
V_b	volume of the burner zone, m^3
Y_i	mass fraction of species i
μ_t	turbulent viscosity, Pa·s
ρ	density, kg/m^3
$\overline{\tau}$	stress tensor, Pa
$\overline{\tau}_e$	effective stress tensor, Pa

cancels the environmental benefits of natural gas compared to coal.

Unfortunately, a large number of small PLSs located in remote areas is not connected to the electric grid. Accordingly, metering information for such objects is provided by local battery-operated devices, not integrated with the operators' dispatching centre (SCADA systems). If a failure occurs in the network, a rapid change of parameters is only registered locally, but it is not immediately reported to the dispatching centre.

The objective of the reported project is to address this problem by providing a small-scale local electric supply in order to enable installation of relevant communication technologies.

The power demand required for the supply of typical metering equipment of a small PLS is not high, and can be estimated in the range of 50–100 W. The lower limit covers a flow converter and a GSM/GPRS communication module, and the upper limit also includes a small-scale electronically-driven odorizing plant. Since the PLS is an off-grid object, it is necessary to provide autonomous power supply for the equipment.

Most of the available solutions for autonomous power supply are related to a larger scale of power. The range of power needed for the present project is below the 'micro-scale' island-mode power supply, representing power output of 1–3 kW. Micro-scale generators may combine renewable and non-renewable sources, and the technical systems may integrate e.g. PV panels, a Stirling engine and a heat storage unit [5], a battery-hydrogen hybrid system [6] or PV, wind and diesel units [7]. Research interest is also dedicated to more complex micro-scale (3 kW) off-grid solutions combining thermal solar systems with hydrogen production and storage and with a fuel cell [8].

In the studied case of natural gas infrastructure, the required power range is very low (as introduced, about 50–100 W). To provide the required power in an island mode it is possible to use PV panels [16], however, in the geoclimatic conditions of Poland and most of the Northern European countries this source alone is not sufficient. On the other hand, gas expanders (e.g. [17]) utilizing the exergy of pressurized gas are also not a suitable solution for island mode operation since their power output is much higher than the local demand (even using the smallest available machines), and the generated electricity needs to be exported. Therefore, within the reported work it was proposed to design a thermoelectric generator (TEG) fired with natural gas available on-site, assuming that the consumed flux of gas is negligible compared to the flux of gas transported.

Due to the low efficiency, TEGs are typically used to convert a small part of the available waste heat to electricity, increasing the overall system performance. Recently, this strategy was studied by Demir and Dincer [9]; the analyzed TEGs were installed inside a shell-and-tube heat exchangers receiving heat from hot flue gas and cooled by seawater. The system was part of a desalination system using both solar power and natural gas. Stobart et al. [10] studied the application of TEG for energy recovery from automotive engine exhaust. The proposed designed comprised thermoelectric (TE) modules installed around the exhaust pipe and were cooled by a liquid coolant flowing through the outer layers or the TEG. A similar solution with the TEG installed downstream of the catalytic converter was studied by Yu and Chau [23] and He et al. [15]. It should be stressed that the electric efficiency of a TEG depends on the material used for the modules [14]. Moreover, most TE module materials have a limited hot-side temperature, which decreases their range of applicability. A possible solution of this problem has been recently proposed by Huang and Xu [11]; the authors develop a concept of a regenerative TEG where the hot gas can be split into multiple fluxes of lower temperature, applicable for the TE modules.

It should be added that TEG may be promising for island-mode electricity generation from solar energy, as reported by Özdemir et al. [25]. Here the flux of heat obtained from a solar collector was supplied to the TE module via a heat pipe, and cooling was provided by a wind chimney. However, the obtained power was only 0.83 W on the hottest day of the year, which shows that the technology readiness level of solar-driven TEGs is still low.

Another particular area of application of TE modules is related to the construction of self-powered temperature sensors as reported by Shi et al. [24].

However, TEG may be also used for island-mode power supply in remote areas. As recently reported by Champier [12], radioisotope TEG were used in the past in Russia for medium-scale power supply (lighthouses) in remote areas, yet no detailed information on these devices is available. Moreover, small-scale TEGs (15–550 W) supplied with heat released from combustion of gaseous fuel are also available in the US/Canadian market [13], yet the cost of this equipment shipped to the EU market (above 200 USD/W) is way too high to be accepted as a standard in the natural gas sector.

The aim of the project reported in this paper is to propose an original design of a TEG dedicated for island-mode power supply of pressure letdown stations in the natural gas distribution sector. It is assumed that the low efficiency of the TEG is acceptable due to the very low power demand. This assumption is particularly justified if the TEG is integrated with PV panels. In such case, both sources (TEG + PV) are complementary in terms of solar conditions.

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