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# Evaluation and optimization of thermoelectric generator network for waste heat utilization in nuclear power plants and non-nuclear energy applications

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ABSTRACT

This paper addresses the development of a waste heat utilization using thermoelectric generator network for nuclear power generation facilities including nuclear power plants such as CANDU and PWR, and Gen-IV reactor designs such as molten salt reactor (MSR). The Thermoelectric Generator Safety System (TEGSS) provides maximum power from the waste heat, which has potential to be used as a backup power source in the event of loss of power following accidents as well as in normal operation. Power is generated utilizing thermoelectric generators which extracts the waste heat energy from the reactor. The power can be used for equipment in the control room or other areas as required to ensure plant status is available at all times for critical decision making during an accident scenario.

## 1. Introduction

Modern nuclear power plants produce heat from nuclear reaction to create electrical power. Water and oil are used to transport heat energy from the power plant to the turbine. During transport, much of the heat energy is wasted. A solution to regain the wasted heat is to place thermoelectric devices, or thermoelectrics, in-line with the path of the fluid. The technology behind thermoelectric devices is the temperature differences between the two plates. An electrical insulator is placed between the two plates. The thermoelectric generators use heat exchanging technology to produce the power; in the order of watts. The temperature of the fluids are relatively low, under 300 °C (Niu et al., 2009). Capturing the excess heat from that area with the thermoelectric generators provides auxiliary energy production (Serway and Jewett, 2004; Thermoelectric Generator Safety System, 2015).

The thermoelectric generator (TEG) network was designed to lengthen the useable life of the Class I & II power supply systems in the Canadian deuterium-uranium (CANDU) reactors, pressure water reactors (PWR), and molten salt reactors (MSR) Chaplin, 2014. These systems consisted of battery banks that were to be capable of maintaining their maximum load functions for approximately 40 min upon the loss of power from upper class (class III & IV) buses (Froats, 2013). Without the Class I & II power supply, monitoring capabilities of the reactor are lost. The purpose of the TEGSS design is to extend the lifetime of the Class I & II batteries in order to provide an increased useful time; hopefully providing sufficient time to regain Class III power to the unit(s).

While evaluating the potential integration locations within a CANDU six nuclear power plants (CANDU, 2012), it was determined that the thermoelectric generator network would be highly applicable in powering auxiliary systems. In an emergency situation, such as the Fukushima incident, the reactor is shut down immediately following loss of class IV power. The steam production of the plant quickly diminishes to an unusable amount for a TEG system. In contrast, it was concluded that the use of the TEG network could have a strong, positive effect towards increasing the secondary side plant efficiency by producing electrical power from waste heat.

More specifically, the purpose of the TEG network design is to directly supply supplemental class IV loads to reduce demand on normal class IV supply. It is more efficient to provide electrical power directly to specific loads than the general plant class IV output, as that would require extensive voltage step ups.

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The purpose of this paper is to evaluate the optimization of the thermoelectric generator network for the CANDU reactors. The research uses commercially-made heat exchanging thermoelectric generators for experimentation on the TEG network. There is a discussion on the theory behind the thermoelectric generator. A discussion of the methodology, in both the simulation and the experimental set-up. The results show the outcomes from the simulations and experiment. The discussion and conclusion sections explain the use of the TEGSS in the CANDU power plants.

## 2. Background theory

Thermoelectric generators function by converting the difference in temperature between two bodies into electrical current by the way of the Seebeck effect. The Seebeck effect occurs where two dissimilar metals have different temperatures. In between the dissimilar metals, there are p and n junction semi-conductors which functions as a barrier. Fig. 1 illustrates the phenomenon (University of Waterloo, N.D).

The Seebeck effect is a function of Ohm's law in which the electromotive force from the temperature difference takes into effect (Yu and Zhao, 2007). Therefore, Ohm's law in the Seebeck effect is the summation of the electric field and the electromotive force,

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{E}_{emf}), \tag{1}$$

where $\mathbf{J}$, $\sigma$, $\mathbf{E}$, and $\mathbf{E}_{\mathrm{emf}}$ are the current density, conductivity, local electric field, and electromotive force, respectively. The electromotive force in the Seebeck effect is the product of the Seebeck coefficient ($S_{Seebeck}$) and the temperature (T) gradient,

$$\mathbf{E}_{emf} = -S_{Sddbeck} \cdot \nabla T. \tag{2}$$

The Seebeck coefficient, also known as thermopower coefficient, is material dependent (Thermoelectric Generator Safety System, 2015).

The thermoelectric generator works as heat exchangers. The semiconducting materials are placed in between the hot and cold fluid channels. As the fluids pass through the channels, the differential temperature causes the production of the electrical power (Çengel and Ghajar, 2010; Chih, 1996).

## 3. Methodology

In this study, simulation and experimental work were conducted. The simulation features a three-dimensional finite element analysis of the fluid flow through the pipes in both parallel and serial configurations. In the simulations, the thermoelectric generator box has been removed for simplicity. The assumptions are discussed further in the paper. The experimental work consists of a single 48 V thermoelectric generator to verify the system, and two 24 V thermoelectric generators configured both in parallel and serial to observe the power generation from each TEG. Fig. 2 shows the 3D-model of the thermoelectric generator.

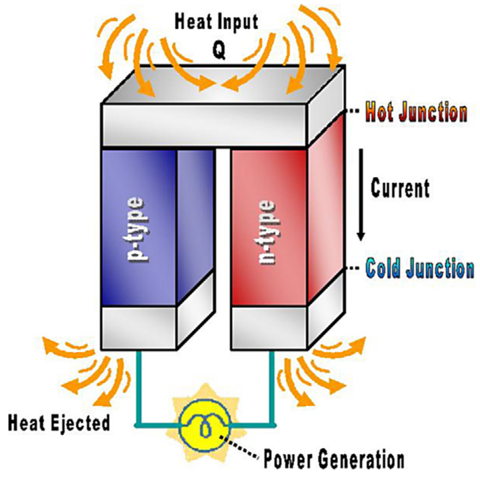

**Fig. 1.** Seebeck effect (University of Waterloo, N.D).

### 3.1. Simulation

The simulation consists of two configurations, mentioned previously in this paper: parallel and serial. The purpose of simulating these configurations is to test the overall power dissipation, in which the thermoelectric generators collects the energy to convert to electrical energy. Figs. 3 and 4 displays the parallel and serial configurations. The parallel configuration consists of three hot fluid channels going through the thermoelectric generators and the fluid combines at the end of the exchange. The serial configuration consists of a single hot fluid channel going through three thermoelectric generators. All the cold fluid channels are independent to the thermoelectric generators.

There are some assumptions made in the simulations in order to ease calculations without sacrificing accuracy:

1. Assuming thin walls of the pipes,
2. Mass flow rate is constant,
3. Ambient pressure is one atmosphere.

Sieman's NX software is used in order to model the simulation in three-dimension. The models are then imported into ANSYS Fluent to use for the simulation. The specifications of the simulation are listed in Table 1.

The Reynolds numbers are calculated in order to find whether the fluid flow is turbulent or laminar. The Reynolds number is (Wendt, 2009; Bar-Meir, 2011)

$$Re = \frac{\rho u D}{\mu}, \tag{3}$$

where $\rho$, $u$, $D$, and $\mu$ are the density, speed, hydraulic diameter, and dynamic viscosity, respectively (Wendt, 2009; Bar-Meir, 2011). The

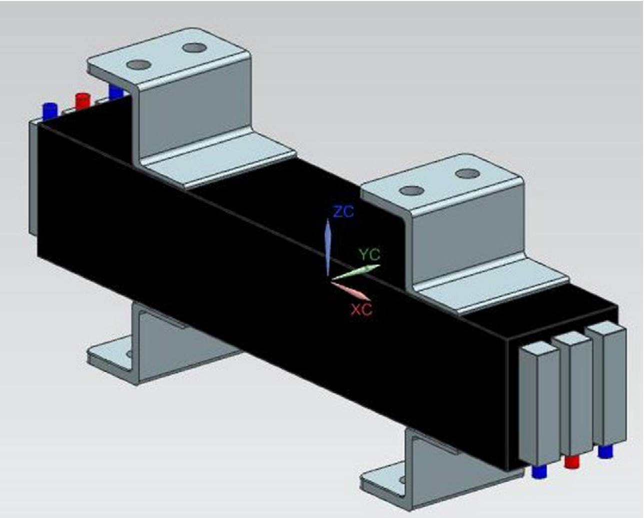

**Fig. 2.** Thermoelectric Generator Unit Model in Siemen's UG NX 9.0. The blue cylinder represents the cold fluid flow while the red cylinder represents the hot fluid flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)