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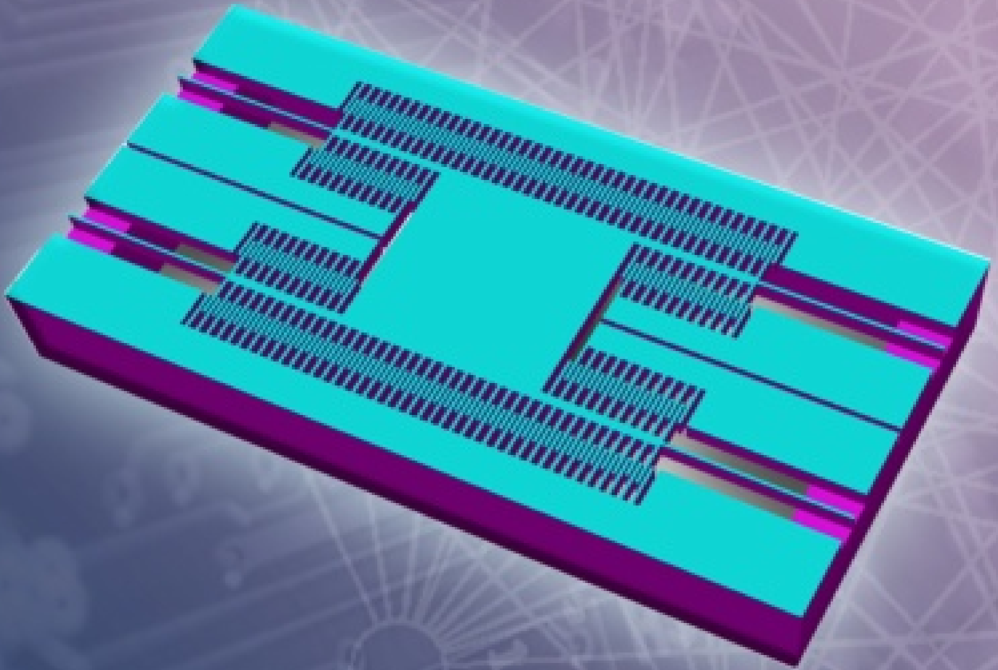

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Utilizing Bi2Te3 TE Pellet as the Condenser of Thermal Power Plant

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Abstract: The efficiency of thermal power plants is rather poor. In the power plants, before starting a new cycle, the steam which is used to spin the turbine in the last cycle has to be condensed to water at first and then reheated to change into steam again. This process is an important thermodynamic rule and needed for an efficient heat to electricity conversion cycle in the power plants, so, in addition to mechanical and heat transfer losses, large amounts of fuel energy is wasted during condensation and rejected to the atmosphere. In the presented paper, we decide to convert some of the condenser wasted energy to electricity using thermoelectric material. At first, the cycle occurring in thermal power plants in which the electricity is generated from the fuel heat, is explained. Then, the two condenser types and their performance mechanism are declared. After selecting appropriate thermoelectric material and presenting its characteristic and also equations, a thermoelectric generator is designed to use as the condenser of a 2000 MW thermal power plant. It's shown that about 3.3 % increasing in the power plant efficiency is expected by using the selected thermoelectric generator in the condensation cycle.
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Keywords: Thermal power plant, Rankine cycle, Condenser, Thermoelectric material.

1. Introduction

The first thermal power plant was built by Sigmund Schuckert in Ettal in 1878. In the power plant a steam engine drove 24 dynamo generators. Thermal power plant, is fossil fuel energy to electricity convertor in which during a cycle, steam is used to spin a turbine driving an electrical generator to produce electricity. (Fig. 1). The cycle is named Rankine cycle including four processes:

1. The water is pumped from low to high pressure.
2. The high pressure water is entered the boiler to become a dry saturated steam with a constant pressure.
3. The steam passes through the turbine and electrical power is obtained from the generator.
4. The cooled steam is condensed to a saturated liquid.

Around 6 % of the generator output power is used for the power plant internal consumption. About 10 % of the losses are during combustion and heat transfer. There are about 5 % losses in electrical generator and about 3 % in the output step-up transformer.

The main 40 % losses in thermal power plant are in condenser where the steam changes in to the water.

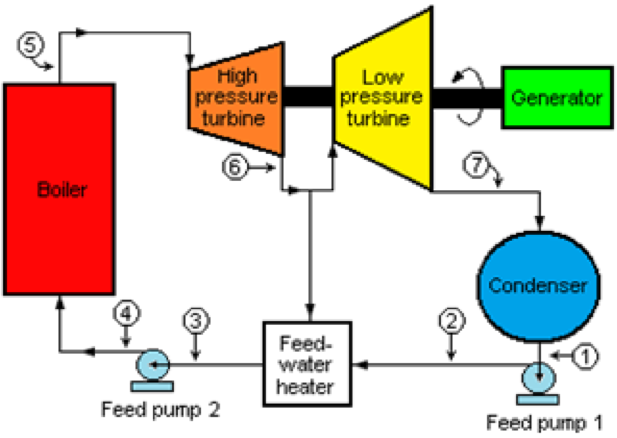

Fig. 1. The internal thermal power plant cycle.

The changing of the steam to the cool water is unavoidable because of the thermodynamic rules of Rankine cycle. In fact, the turbine receives the steam energy which is given to the water in the boiler. In other word, if the water be cooler, it picks up more energy to be a dry steam so the energy which is given to the turbine by the steam is more and as a result, the performance and the efficiency of the cycle are better. By now, the steam heat which is taken by the condenser is wasted to atmosphere [1, 2]. In this paper, we decide to design a thermoelectric (TE) generator to produce electricity from some amount of the wasted heat in the condenser. TE generators are heat to electricity directly convertors. Their conversion is due to an effect named TE (Seebeck) effect which is discovered in 1821. They were first only used in thermocouples to measure temperature. But discovering materials with much more TE effect made TE materials useful for refrigeration and also electricity generation [3, 4].

By using TE generator there is no need to cooling tower, lake or ocean to cool the condenser. In the designed system, the TE pellets take the steam heat, convert some of the heat to electricity and reject the rest of the heat to the atmosphere which is made them hot so airflow should use to cool the outer side of the TE pellets.

The presented TE generator is designed for a 2000 MW thermal power plant. It is calculated that by using the designed TE generator, the efficiency of the selected power plant increases from 33 % to 36.33 %.

2. The Rankine Cycle

In Rankine cycle which is shown in Fig. 2, the water is entered and circulated in the boiler tubes in furnace where the fuel combustion is occurred. Typically the efficiency of this process is around 90 %. The reasons of the losses are:

- Since limitations in heat transfer, all of the produced heat is not transferred to the water.
- Some fuels like coal contain moisture and hydrogen taking latent heat from the combustion energy in the furnace and exit as hot gases [2]. As the water is circulated in the boiler tubes, it absorbs heat and changes in to the steam with about 371 °C temperature. The steam is separated from the water inside a drum at the top of the furnace. The drum has some devices inside removing moisture from the wet steam to prepare dry steam.

The saturated dry steam is then entered into superheat pendant tubes to form a superheat Rankine cycle. In superheat tubes where is the hottest part of the furnace the steam picks up more energy. Here the steam is heated up to around 500 °C which is above the saturation temperature. In normal Rankine cycle, as the steam passing the turbine, it's condensed and the water droplets hit the turbine blades decreasing the turbine life and efficiency. As it's shown in Fig. 2, steam superheating is the best solution to overcome the problem. In fact, by superheating the steam, Wturbine and as a result, the efficiency increase. So, the higher steam temperature, the higher efficiency.

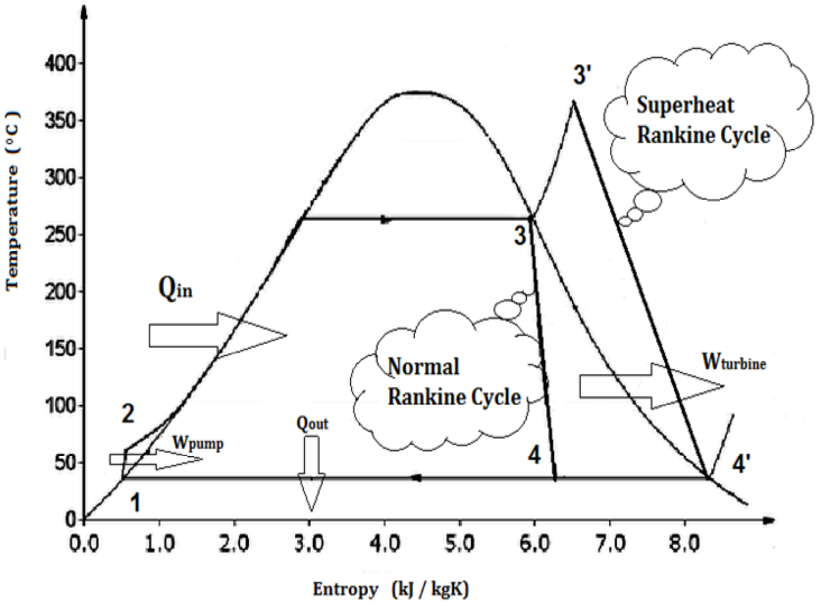

Fig. 2. Normal and superheat Rankine cycle.

The superheated steam is then piped to high pressure turbine. The high pressure turbine at one end is followed by an intermediate pressure turbine and then low pressure turbine which is connected to the electrical generator. The superheated steam passes through the turbine and losses its pressure and also thermal energy. The turbine drives the electrical generator. The generator voltage ranges from 11 kV in smaller units to 22 kV in larger units. The generator high voltage leads which are normally large aluminum channels are connected to step-up transformer for connecting to a high voltage electrical substation for further.

After passing through the turbine, the steam is condensed in a condenser, changed in to the water and then pumped back to the boiler.

The efficiency of Rankine cycle which is named thermodynamic efficiency can be declared as:

$$\eta_T = \frac{W_{turbine} - W_{pump}}{Q_{in}} \approx \frac{W_{turbine}}{Q_{in}}, \quad (1)$$

where $W_{turbine}$ is the turbine produced power in process 3-4 given to electrical generator, W_{pump} is the consumption power of the water pump in process 1-2 and Q_{in} is the heat energy given to the water in process 2-3.

In an ideal Rankine cycle, the pump and turbine would generate no entropy, so the processes 1-2 and 3-4 would be done on vertical lines. As a result, the maximum electrical power is generated.

In a real Rankine cycle, these processes are non-reversible and the entropy is increased during the two processes which on one hand, increases the pump required power, on the other hand, decreases the turbine generated power and produced electrical power as well [5, 6].

3. Thermal Power Plant Condenser

The thermal power plant condenser shown in Fig. 3 consists of shell and tube heat exchanger in which the exhaust wet steam of the low pressure turbine is entered the shell and cooling water is circulated through the tubes. The steam heat is absorbed by the cooling water which condenses the wet steam in to the water with about 35 °C temperature.

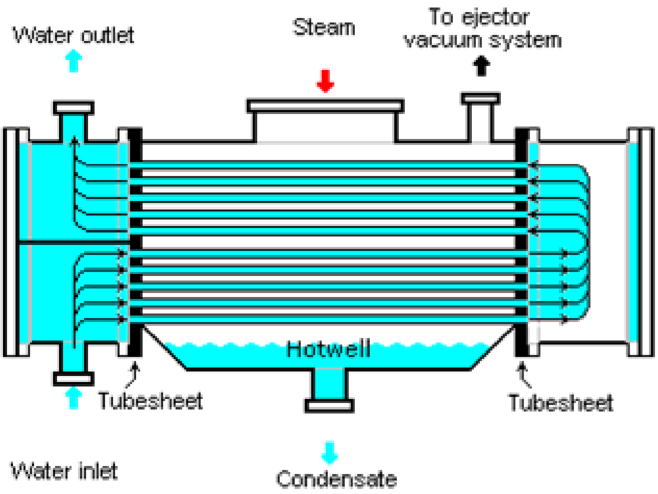

Fig. 3. Thermal power plant condenser.

The large decreasing in volume which occurs during condensation creates a low vacuum that helps pulling steam through and increases the efficiency of the turbine.

The temperature of the cooling water is kept in about 11 to 17 °C by circulating it in a cooling tower or water from a river, lake or ocean to reject the wasted heat to the atmosphere.

If the condenser makes the water cooler, the pressure of the exhaust steam is reduced and the efficiency of the cycle is increased [7].

Another form of condensation system is the air-cooled condenser in which exhaust steam of the low pressure turbine runs through the condensation tubes which are usually finned. The air is pushed through the fins and the steam is condensed to water. Air-cooled condensers typically operate at a higher temperature than water-cooled versions so their efficiency is less than water condensers [8].

Almost 40 % of the input energy is lost during the condensation process where the energy of the steam is rejected to the atmosphere. This is the major loss in the thermal power plant.

4. Thermoelectric Generator

TE materials are used for refrigeration and electricity generation. TE generator which is shown in Fig. 4 is a direct thermal energy to electricity convertor. Since the TE effect, a small voltage is created between the TE generator terminals by the temperature difference between its two sides.

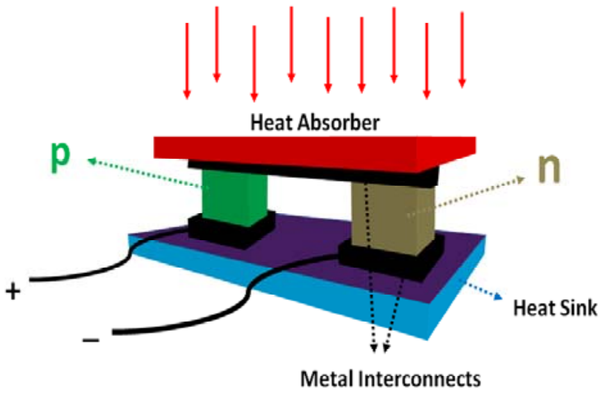

Fig. 4. Thermoelectric generator structure.

The TE effect exists in all materials but most of them have insignificant TE characteristics. The TE generators performance and also efficiency depend on their material figure-of-merit (ZT), which is shown in Fig. 5. ZT is calculated as follows [3, 4]:

$$ZT=\alpha^2\sigma T/\kappa, \tag{2}$$

where α (V/K) is the material Seebeck coefficient, σ (S/m) electrical conductivity and κ ($W.m^{-1}.K^{-1}$) is thermal conductivity. Electrical resistivity of the material ρ (Ω.m) can be obtained from electrical conductivity:

$$\rho=1/\sigma \tag{3}$$

The thermal conductivity is sum of the component carrier (electron) and phonon which are respectively, $\kappa_{electron}$ and κ_{phonon}:

$$\kappa = \kappa_{electron} + \kappa_{phonon} \tag{4}$$

According to The Wiedmann-Franz law the carrier thermal conductivity is given as:

$$\kappa_{electron} =L.\sigma.T \tag{5}$$

where, L is the Lorenz number ($2.445\times10^{-8}W.S^{-1}.K^{-2}$) [9].

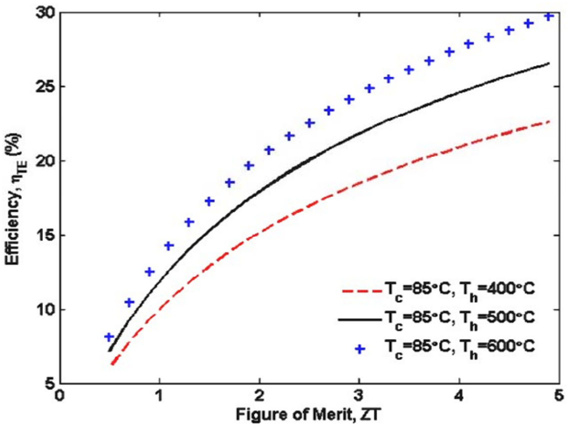

Fig. 5. Efficiency versus figure of merit.

The best TE materials are called “phonon-glass, electron-crystal” (PGEC), which means that the materials with low thermal conductivity as in a glass, and a high electrical conductivity as in crystals are desired, while because of the physical characteristics of usual TE materials, these two parameters change in a similar way. So, the improvement of the TE materials ZT and also efficiency is so hard [10]. But current researches on nanocomposite materials show that their ZT (and also their efficiency) is able to improve [11].

According to (2) and also the units of α and κ, ZT changes with temperature variation. In fact, the amount of the ZT, in the desired temperature, is one of the most important parameters to choose a TE material.

5. Thermoelectric Generator Equations

The basic performance equations of TE generator are explained here [12].
The temperature difference between the hot and cold side of the TE generator is:

$$\Delta T = T_H - T_C \tag{6}$$

where, T_H is the hot side and T_C is the cold side temperature in Kelvin.

The open circuit output voltage is:

$$V_{oc} = \alpha \cdot \Delta T \tag{7}$$

So the output current is calculated as follows:

$$I = V_{oc} / (R + R_L), \tag{8}$$

where R is the TE generator internal resistance and calculated as:

$$R = \rho l / A \tag{9}$$

where l is the length and A is the cross sectional area of the TE pellet.

RL is the load resistance which is set 1.323393R, for optimum efficiency [12].

The output power is:

$$P=I^2 . R_L \tag{10}$$

The input heat to the TE generator is calculated as follows:

$$Q_H = \alpha.I.T_H - 0.5R.I^2 + K. \Delta T, \tag{11}$$

where K is:

$$K= \kappa.A / l \tag{12}$$

So the TE pellet wasted heat is:

$$Q_C = Q_H – P \tag{13}$$

and the TE pellet efficiency is:

$$\eta = P / Q_H \tag{14}$$

6. Thermoelectric Steam Condenser Design

Here we select a 2000 MW thermal power plant. The efficiency of thermal power plant is typically around 33 % so the input fossil fuel energy (P_f) is:

$$P_f = 2000 / 0.33 \approx 6060.6 \text{ MW} \tag{15}$$

About 40 % of the input energy is wasted during the condensation process. So the input energy of the condenser (P_C) is calculated as:

$$P_C = 6060.6 \times 0.4 \approx 2424.25 \text{ MW} \tag{16}$$

Nanowires 6×6×1 mm bismuth telluride (Bi2Te3) TE pellet is selected for the designing. Its Seebeck coefficient is 287 μV/K at 327 Kelvin. It has high electrical conductivity of 1.1×105 S/m and very low lattice thermal conductivity of 1.20 W.m-1.K-1. Its melting point is about 858 Kelvin and it's useful in temperature between 300 to 400 Kelvin [13, 14].

The material figure-of-merit, from (2), is:

$$ZT= [(287 \times 10^{-6})^2. (1.1\times10^5). (327)] / (1.20) = 2.47 \tag{17}$$

Here, the temperature of the wet steam entered the condenser which is also the temperature of the hot side of the TE pellet, is supposed: TH =400K. The temperature of the cold side of the TE pellet is: TC = 300 K, so from (6) and (7):

$$\Delta T=400 -300 = 100 \text{ K} \tag{18}$$

$$V_{oc}=(287 \times 10^{-6}). 100 = 28.7 \text{ mV} \tag{19}$$

From (3), the electrical resistivity is:

$$\rho = 1/\sigma = 1 / (1.1\times10^{5}) = 9.09 \times 10^{-6}\ \Omega.\mathrm{m} \tag{20}$$

From (9), the internal resistance is:

$$R = (9.09 \times 10^{-6}).\ (1\times10^{-3}) / (6\times6\times10^{-6}) = 0.252\ \mathrm{m} \tag{21}$$

So R_L is:

$$R_L = 1.323393R = 0.334\ \mathrm{m}\Omega \tag{22}$$

As a result, from (8) and (10):

$$I = (28.7) / (0.252 + 0.334) = 48.98\ \mathrm{A} \tag{23}$$

$$P = (48.98)^{2}.(0.334\times10^{-3}) = 801.28\ \mathrm{mW} \tag{24}$$

From (12) and (11), K and the pellet input heat power is:

$$K = [(1.20).\ (6\times6\times10^{-6})] / (1\times10^{-3}) = 0.0432 \tag{25}$$

$$Q_H = [(287 \times 10^{-6}).(\ 48.98).(400)] - [0.5\ (0.252\times10^{3})\ (48.98)^{2}] + [(0.0432).\ (100)] = 9.640\ \mathrm{W} \tag{26}$$

The wasted heat is calculated from (13):

$$Q_C = 9.640 - 0.801 = 8.839\ \mathrm{W} \tag{27}$$

So the efficiency from (14) is:

$$\eta = (0.801/\ 9.640) \times 100 = 8.31\ \% \tag{28}$$

As $P_C = 2424.25$ MW, so the output power of the TE generator (PCout) is:

$$P_{Cout} = 2424.25 \times (8.31 / 100) \approx 201.505\ \mathrm{MW} \tag{29}$$

The number of pellets needed to produce the power is:

$$N_R = (201.505 \times 106) / (0.801) = 251{,}566{,}791.5 \approx 251{,}566{,}792 \tag{30}$$

The area needed for 251,566,792 pellets:

$$S_R = 251{,}566{,}792 \times (6\times6\times10\text{-}6) = 9056.405\ \mathrm{m}^{2} \tag{31}$$

The total output power of the power plant is now:

$$P_{O\ total} = 2000+201.505 = 2201.505\ \mathrm{MW} \tag{32}$$

The total efficiency of the thermal power plant is calculated as:

$$\eta_{total} = 100 \times 2201.505 / 6060.6 \approx 36.33\ \% \tag{33}$$

7. Conclusion

The major losses of thermal power plants are in condensation cycle in which the wet steam changes in to the water after spinning the turbine. In the cycle which is an unavoidable cycle, about 40 % of the input fuel energy is wasted.

In the paper, Bi2Te3 nanowires material is used as TE generator in the thermal power plant condenser to convert some amount of the low pressure turbine exhaust steam heat to electricity. The figure of merit and also the operational temperature of the TE materials are important factors to choose a TE material for a particular application. The maximum figure of merit of the selected TE material is in the temperature of about 327 K which is around the temperature of the wet steam entered the condenser.

It was calculated that by using the designed TE generator, about 201.505 MW of the wasted heat in the 2000 MW thermal power plant could be converted to electricity. The designing increased the electricity generation efficiency for about 3.3 %.

The efficiency of the selected TE material was calculated about 8.31 %. Using new and more efficient TE materials as power generations in the condensation cycle of thermal power plant is offered as a future work.

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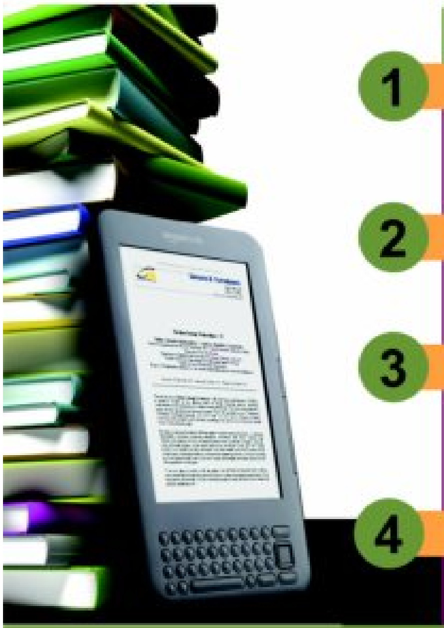

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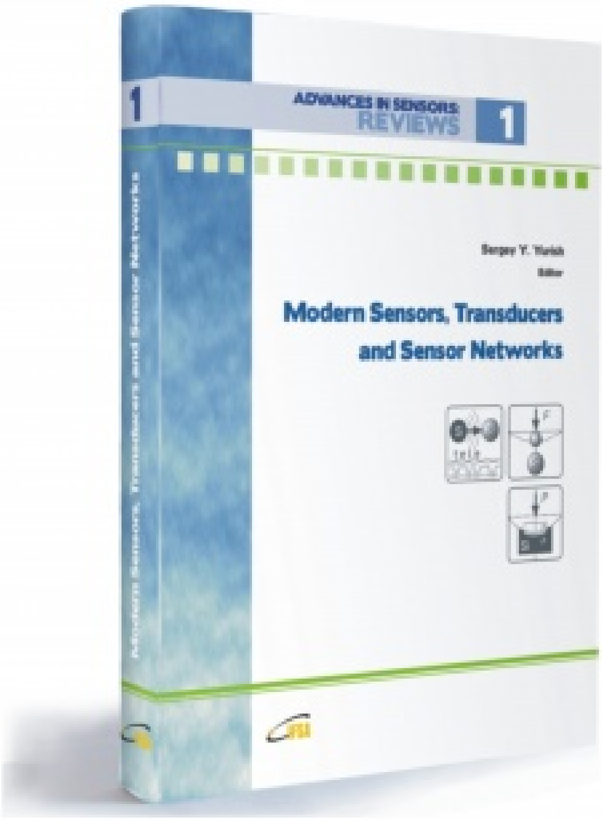

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