HEAT EXCHANGERS

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Contents

Summary

The chapter is concerned with scientific and practical aspects of a big variety of Heat Exchangers, their application and designing problems.

1. Introduction

A heat exchanger is an apparatus in which heat transfer from one (hot) fluid to another (cold) fluid occurs. The heat transfer device, used since the dawn of civilization, is a simple boiler for preparation of food, placed above an open fire. Heat exchangers, i.e. heat transfer equipment for technical purposes have been devised only with emerging of a steam machine mostly towards the end of the 19th century and early 20th century. The elementary steam boiler may be regarded as the first heat exchanger. It is a closed vessel, filled with water heated by an open flame. Heat is transmitted to water through the wall of the boiler to heat it and generate steam. The use of heat for technical purposes stimulated the creation of a science about heat exchange. I. Newton's work in1701, in which the process of heating of a solid body by the stream of a hot liquid was studied, may be regarded as the first scientific investigation in this direction. A systematic development of the studies of heat propagation processes began in the 19th century. The researches have shown that the complex process of heat transfer can be divided into three modes. The first mode is conduction. The heat is transmitted at molecular level through direct contact of elementary particles without mass movement as a whole. The law of a thermal conduction was formulated by B.J. Fourier in 1822. The amount of heat, Q_λ transmitted by a thermal conduction is given by the expression

$$Q_\lambda = -\lambda \; gradT \; F\tau$$

The second mode characterizes the process of heat transfer between a liquid (gas) and wall in a case, when there is a difference of temperatures between the liquid and the wall. The heat is transferred mainly through the intermixing and transposition of particles in space, but is partial by thermal conduction. The convective heat exchange is complex with heat and mass flows. Rigorous analytical solutions are obtained for the limited number of cases. In practical engineering the amount of heat Q_c transmitted by convection is determined by the Newton equation:

$$Q_c = \alpha F (T_l - T_w)\tau \; .$$

Convective heat transfer coefficient α mainly is found from model experiments, which outcome is treated with the Theory of Similarity methods.

The third mode of heat transmission is radiation. The nature of this phenomenon is based on the fact, that all materials at temperature above absolute zero emit energy in the form of electromagnetic waves. The thermal energy at first is converted into radiant energy, and then back to thermal form. The radiant energy calculation is based on the Stefan – Boltzmann's law (1879-1881). The amount of heat Q_r emitted from the surface of an ideal black body is

$$Q_r = \sigma_r F T^4 \tau \quad ,$$

where σ_r is the Stefan-Boltzmann constant.

In general the total amount of heat transferred is given by the sum of heat flows by thermal conduction, convection, and radiation. Depending on real conditions the relative proportions of these heat flows vary.

Modern methods of heat transfer science and engineering enable us in creating highly effective heat exchangers for different purposes.

2. Heat Exchanger Role in Gas Turbine Units

In a thermodynamic cycle of any heat engine addition of heat to a working medium from heat source and rejection of heat from the working medium to heat sink take place. In gas turbine complex cycles some heat sources and some heat sinks can be involved simultaneously. The admission of heat can be carried out as a result of fuel burning into the working medium (open cycle) or from an external source through heat exchangers. The rejection of heat can take place as an outcome of exhaust of the hot working medium into ambient atmosphere or to a heat sink through heat exchangers.

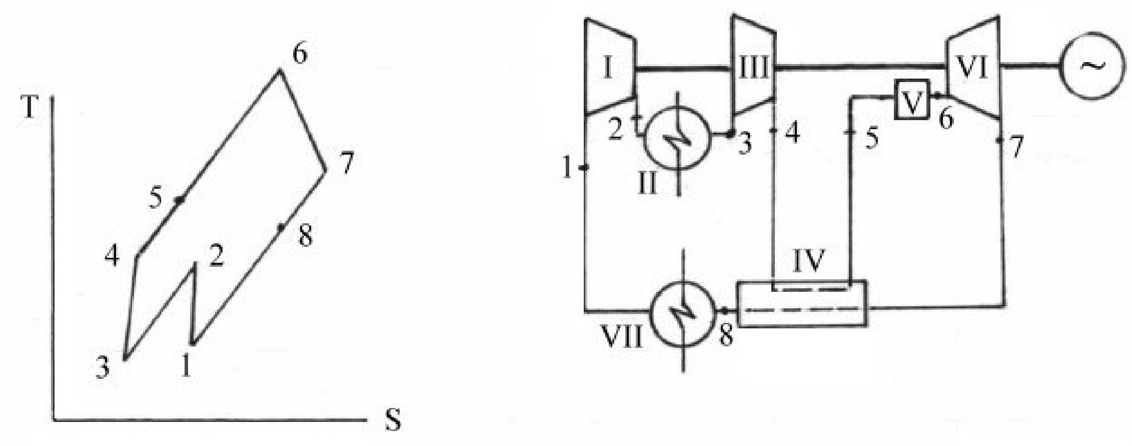

Figure 1. Thermodynamic cycle and typical scheme of direct cycle and turbine unit.

The thermodynamic cycle and typical scheme of a gas turbine unit are shown in Figure .1.The working medium is compressed in the low-pressure compressor I (process 1-2), cooled in the intercooler II (process 2-3), compressed in the high pressure compressor III (process 3-4), heated up by heat which is extracted from exhaust gases in the regenerator IV (process 4-5), heated up in the combustion chamber V by burning fuel (process 5-6), expands in the turbine VI (process 6-7) and at last is cooled in the regenerator IV (process 7-8). In open cycle gas turbine units the process of cooling (8-1) takes place in the atmosphere. In closed cycle gas turbine units the process of cooling (8-1) is carried out in the precooler VII and the process of heating (5-6) in the high-temperature heater from an external heat source or in the high-temperature gas-cooled nuclear reactor (HTGR), which are installed instead of the combustion chamber.

Note: A regenerator is a heat exchanger for regenerative use the heat of exhaust gases.

The thermodynamic cycle and the typical scheme of an indirect cycle gas turbine unit (also known as cycle with admission of heat on exhaust) is shown in Figure 2. The main feature of the scheme is the transition of the combustion chamber VI in an item between the turbine V and high-temperature heater IV. It allows burning in the combustion chamber coal and other grades of solid fuel without fear of erosive damage to turbine blades, as the turbine (process 3-4) works on pure hot air. The air is compressed by the compressor I (process 1-2), heated up to temperature T_3 in the heater II, expands in the turbine III. T_5 exceeds T_3, which results in increased temperature T_6 of exhaust. For increase of installation efficiency the waste heat recovery heat-exchanger V (process 6-7), can be included in the scheme.

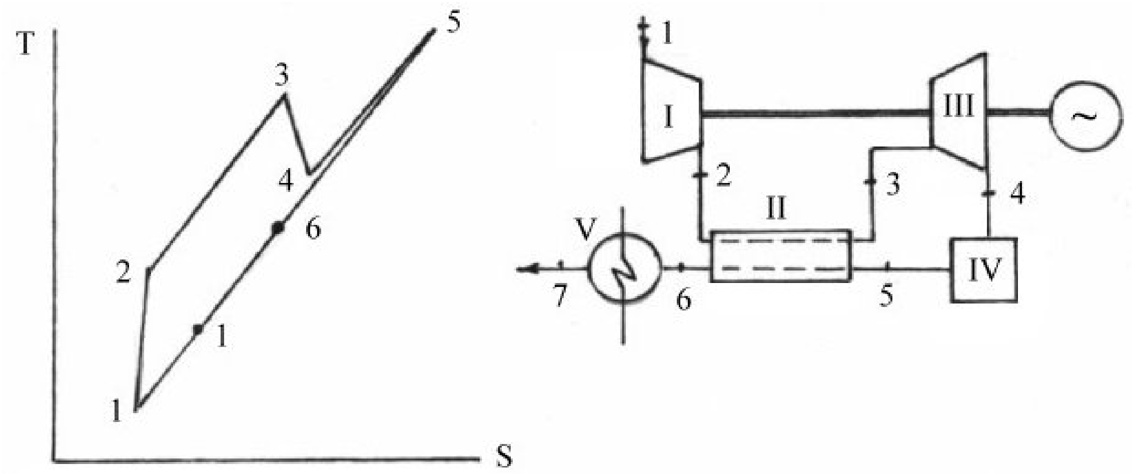

Figure 2. Thermodynamic cycle and the typical scheme of an indirect cycle gas turbine unit (with admission of heat on exhaust)

The thermodynamic cycle and typical scheme of the closed cycle gas turbine unit for space installation is shown in Figure 3. It consists of the compressor I, regenerator II, heat source III, turbine IV and radiator V for heat reject into the open space by radiation. A nuclear reactor or radiation of the Sun can be used as heat source III. In the latter case solar energy concentrator, receiver and heat accumulator (for use during the shadow part of the Orbit) have to be included in the scheme of the installation.

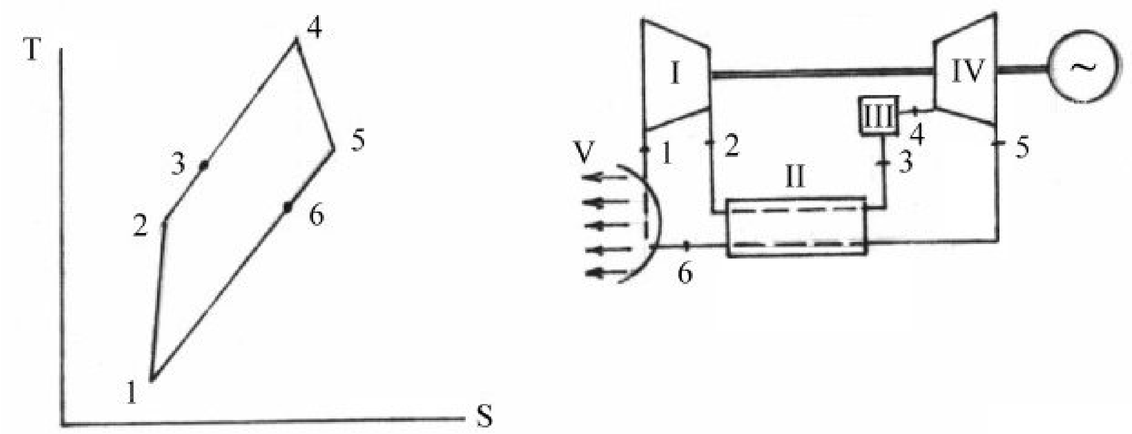

Figure 3. Thermodynamic cycle and typical scheme of the closed cycle gas turbine unit for space installation

The simplest combined steam-gas turbine installation and its thermodynamic cycle are shown in Figure 4. Ordinary gas turbine module (consisting of the compressor I, combustion chambers II and turbine III) is used in the upper part of the thermodynamic combined cycle. The heat exchanger (consisting of the steam superheater IV, steam generator V and the economizer VI) for heat recovery is installed in the exhaust from the gas turbine. The generated steam circulates in a closed loop of the steam turbine unit. After expansion in the turbine VII steam is condensed in the condenser VIII. The steam turbine unit is used in the lower part of the thermodynamic cycle. All figures on the scheme correspond to figures on the cycle diagram.

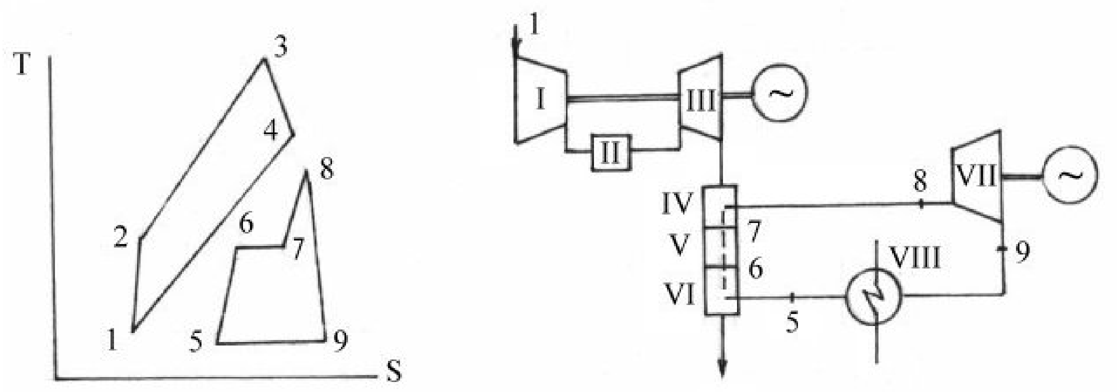

Figure 4: Thermodynamic cycle and principal scheme of combined steam-gas installation

A number of auxiliary systems, where heat exchangers are used, are also included in a gas turbine unit structure. Oil coolers are used in regulation and lubrication systems, fuel preheaters can be used in fuel supply systems (for high viscosity fuel), and air precoolers are often used in gas turbine blade cooling systems (to decrease the air consumption in the system). Other auxiliary systems are possible (for example anti-ice systems), where heat exchangers can also be used.

On the basis of the functional roles and positions, the above considered heat exchangers can be divided into three main groups:

1. Heat exchangers with the help of which the required configuration of a thermodynamic cycle can be realized: precoolers, intercoolers, regenerators, high temperature heaters and preheaters, radiators, etc;
2. Heat exchangers with the help of which combination of gas turbine and steam turbine units as combined steam-gas turbine installations is possible: economizers of feed water, heat recovery steam generators, steam superheaters;
3. Auxiliary heat exchangers: oil coolers, fuel heaters, air coolers, water heaters, steam recovery boilers, etc.

3. Types of Heat Exchangers. Principle of Operation

On the basis of their operational principles heat exchangers can be divided into contact and surface types. In heat exchangers of contact type, the process of heat transfer from the hot working fluid to the cold one occurs by direct contact of the working fluid and is accompanied by mass-transfer process. An example of contact type heat exchanger is the cooling tower, which is used often in steam power plants for cooling of water. In heat exchangers of surface type, the working fluids do not contact each other during the heat transfer process, and the heat transfer surface with which working fluids have to be in contact, plays an active role. The heat exchangers of surface type are further divided into recuperative and regenerative types. In the field of gas turbines the surface type heat exchangers is used mainly.

In the recuperative type heat exchanger, which is shown in Figure 5, the working fluids 1 and 2 flow in spaces separated by a wall 3 (named as heat transfer surface), and heat exchange process takes place by convection from fluids to the wall and by conduction through the wall.. The heat transfer surface (or a matrix of the heat exchanger) is spaced inside bodies 4. The manifolds 5 to deliver and 6 to divert the working media are joined to the body. This heat exchanger is of the direct transfer type as the heat exchange process occurs straight between the working fluid which flows steadily and continuously through the heat exchanger.

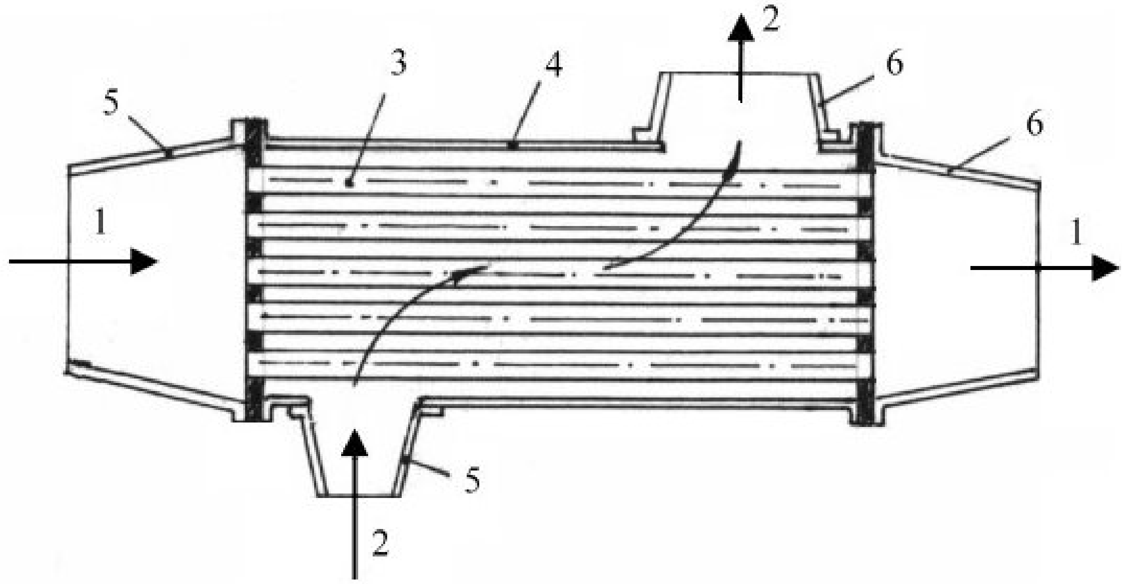

Figure 5: Recuperative type heat exchanger

The coupled heat exchanger scheme (indirect type exchanger) is shown in Figure 6. It consists of two direct type heat exchangers (warmer 1 and colder 2) coupled by pipe contour 3 (filled with an intermediate fluid as water, organic compounds or liquid metals). For circulation of the intermediate fluid, the circuit is equipped with a circulating pump 4. Heat flux from the warmer level heat exchanger is transmitted through the circuit to the colder level heat exchanger.

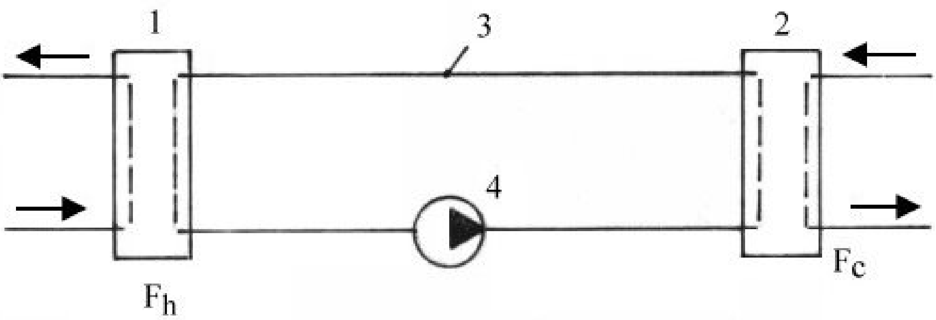

Figure 6: Coupled heat exchanger scheme

In the regenerative type heat exchanger the flow of heat is intermittent. This type of heat exchanger is also called as the periodic flow heat exchanger. At first matrix comes into contact with the warmer working fluid (period of heating): the matrix is heated up and accumulates heat, but the working fluid is cooled. Then at the second (period of cooling) the matrix comes into contact with the colder working fluid (period of cooling): the matrix returns accumulated heat and is cooled, and the colder working fluid is heated up.

The regenerative type heat exchangers are produced either with a stationary or rotating matrix. The scheme of the heat exchanger with a stationary matrix (for example a two-matrix heat exchanger) is shown in Figure 7.

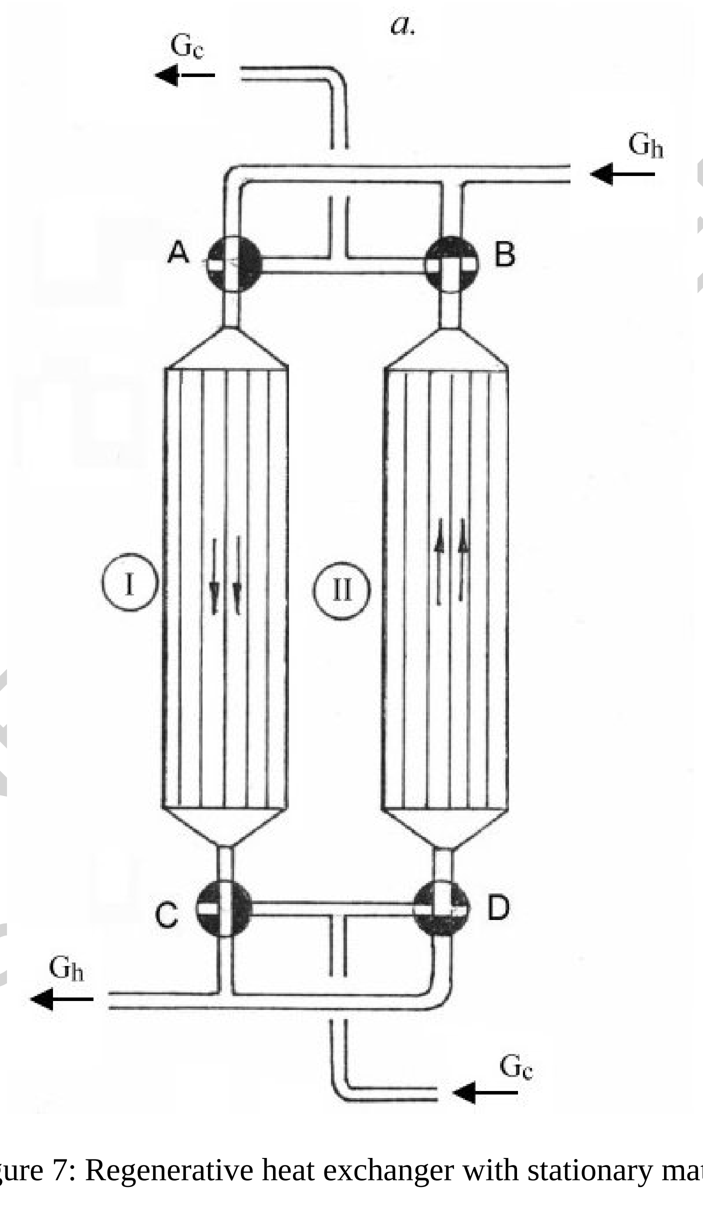

Figure 7: Regenerative heat exchanger with stationary matrix

During a heating period of the matrix I (the warmer working fluid G_h flows through it) the matrix II is cooled by a stream G_c of the colder working fluid. Then streams of working fluids are changed-over by means of the valves A, B, D, E, and the process of heat transfer is alternated. The scheme of the heat exchanger with a rotating matrix of a disk type is shown in Figure 8. The rotating matrix 1 is spaced inside the body 2 which is equipped with the manifolds 3 for warmer 4 and colder 5 working fluids. The flow passages are suitably sealed from each other. The elements of the matrix continuously move from the zone of heating into the zone of cooling and vice versa. The warmer working fluid flows through the matrix in the heating zone, and the colder working fluid flows through the matrix in the cooling zone. The amount of heat transferred through a regenerative heat exchanger depends upon a mass and the thermal capacity of the matrix, and also duration of heating and cooling periods.

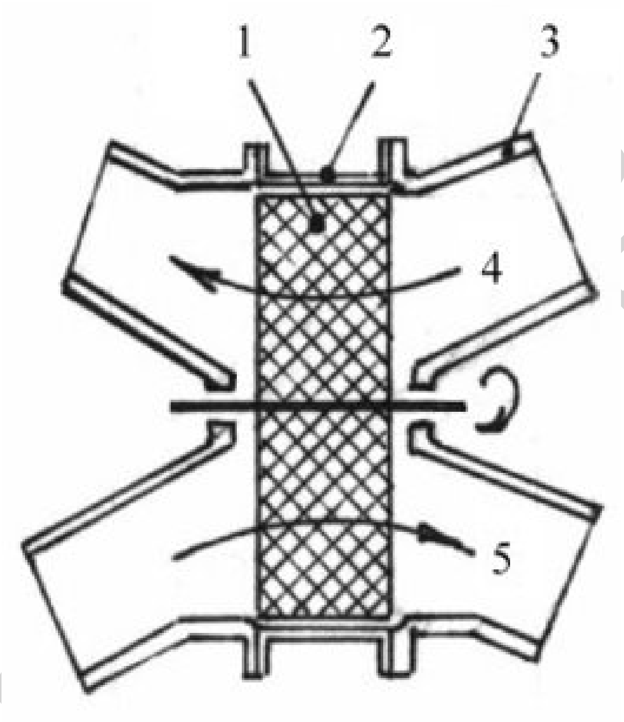

Figure 8: Regenerative heat exchanger with rotating matrix

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Biographical Sketch

Vadim L. Ivanov Ph. D. (Eng) is an associate professor of Gas Turbine Engineering Department of Moscow State Technical University name of Bauman. He was born in 1929 and graduated from Moscow State Technical University name of Bauman in 1954, received Ph. D. in 1960. Associated Professor of Gas Turbine Engineering Department of Moscow State Technical University named after Bauman. He authored more than 150 publications in the field of gas turbine and heat transfer including some text-books.