

The criteria for evaluation of efficiency of heat technical installations considering general energy costs with the aim of increasing their environmental friendliness and reducing negative effect on the environment

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Abstract. The features of the physical meaning of the thermal coefficient useful action (CUA) η_t as a criterion for the efficiency of reversible direct circular processes are considered. In particular, we demonstrate that accounting for all energy costs when applying η_t is made by adopting a number of assumptions by default. In order to expand the possibilities for conducting thermodynamic assessments of the efficiency of various thermal power plants, a new criterion of efficiency K_u is proposed as a coefficient that takes into account in a comparable form all types of energy spent on the implementation of the cycle. In determining the criterion K_u , useful effect obtained from the implementation of a direct circular process is considered to be the specific work of the expansion of the working fluid in the cycle. Such work, in particular, can be the work of steam expansion in the turbine. The total energy cost is the sum of the specific heat supplied to the working body in a circular process and the specific mechanical work spent in the cycle on compression and pressure increase of the working body. In particular, the work is taken into account in a comparable form-taking into account the heat that was spent on its production. The analysis of the K_u criterion is carried out. As a result of the analysis we have established that at transition from the general physical model of reception of specific work of expansion in direct circular process for which K_u criterion can be applied, to the special case assuming a number of assumptions, K_u criterion can become equal to thermal coefficient useful action of a cycle. Using the K_u criterion, the efficiency of Carnot and Rankine cycles on a saturated pair is compared. The K_u score showed that the Rankine cycle was more efficient.

1 Introduction

In thermodynamics by means of reversible circular processes work of various heat technical installations (HTI), in particular internal combustion engines, steam-power installations, refrigerators and thermal pumps is modeled [1, 2]. The efficiency of direct and return cycles decides on the help of various criteria [3, 4]. These criteria allow to choose the most effective which reduce the general fuel consumption from a number of options of technical solutions, so, provide big environmental friendliness of processes [5, 6].

When determining criterion of efficiency of any heat technical installation two additional concepts are entered, as a rule: useful effect and costs of realization of the process providing achievement of useful effect [7-9]. Usually understand quantitatively certain result achieved thanks to heat technical installation according to the destination as useful effect. Expenses usually are understood as the sum of all or main resources necessary

for a possibility of achievement of useful effect on this heat technical installation. In that case the criterion of efficiency can be defined as the relation of useful effect to expenses [10, 11].

In various heat technical installations useful effects can differ very [12, 13]. So, for example, for heat treatment furnaces as useful effect the amount of heat brought to a working body – the gas mix moving in the operating volume of the furnace which provides performance of a necessary condition of successful heat treatment of material can be accepted – increases temperature of a working body to the required level [14].

Traditionally in thermodynamics the efficiency of direct circular processes is estimated by means of the thermal coefficient useful action (CUA) η_t . When determining η_t as useful effect specific work of all cycle l_{cyc} , and as expenses – the warmth of q_{br} brought to a working body in a cycle is considered:

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$$\eta_t = \frac{l_{cyc}}{q_{br}}, \quad (1)$$

2 Methods

The basic method is the theoretical analysis of the efficiency of reversible circular processes. This method provides a comparative analysis of the effectiveness of direct cycles. The method is based on the adoption of the following provisions. The thermodynamic result of a direct circular process is that the thermodynamic system, in which the cycle is realized, is supplied with energy from the environment in the form of heat q_{br} , and the system transfers to the environment a certain amount of energy in the form of mechanical work l_{cyc} and a certain amount of energy in the form of heat q_{wi} . In the process of heat supply to the system, the temperature of the system is higher than in the process of heat removal. In the course of any cycle, the working body in some parts of it performs the work of expansion, in others – compression. The total work of the cycle will be equal to the difference between the total work for the cycle of expansion l_{ex} and the total work of compression l_{com} :

$$l_{cyc} = l_{ex} - l_{com}. \quad (2)$$

From (2) follows the following position, underlying the proposed method: for the implementation of a direct circular process is necessary to supply the working body from the environment, not only energy in the form of heat q_{br} , but also in the form of mechanical work to compress the working body l_{com} . At the same time, from the traditional formula (1) for thermal coefficient useful action, it follows that only the costs of energy supplied to the working body in the form of heat q_{br} are taken into account as energy costs. In this case, the cost of mechanical energy for compression is taken into account as follows. By default, it is assumed that a part of the mechanical energy of the expansion l_{ex} performed by the working body is somehow conserved in the environment during this expansion. After the expansion has been completed and the compression has begun, this mechanical energy, preserved in the environment, is brought to the working body without loss in some way by means of some devices. As a result, the necessary compression of the working fluid in the circular process is provided and the work of compression of the l_{com} is performed. Thus, all the work of the l_{ex} expansion is somehow divided into two parts: one is transferred to the environment for free use, the second is first conserved and then, when the time comes, used to compress the working body. The proposed method of analysis allows estimating the efficiency of a direct circular process to take into account all types of energy costs, without involving any additional assumptions.

3 Results

In a number of cases, the implementation of direct circular processes, for example, in steam-power

installation (SPI), in which to increase the pressure of the working fluid consumes electrical energy supplied to the drive of the feed pump, the above traditional scheme of assumptions is not strictly fulfilled [15]. In such cases, it is advisable to be able to evaluate the effectiveness of direct cycles without introducing the preliminary assumptions described above. This purpose can be used a new criterion of efficiency, in which the useful effect is considered all the work expansion of the working fluid l_{ex} , and as cost – the total cost of implementing a cycle consisting of two types of energy conducted to the working fluid from the environment in the form of heat q_{br} in the form of mechanical work to compress the working fluid l_{com} . Such criterion of efficiency should be called the coefficient considering all costs and to designate as Ku .

That in circular process comparably to put energy in the form of warmth q_{br} and energy in the form of mechanical work of l_{com} it is necessary to consider nonequivalence of warmth and work. In any heat engine, as we know, only a part from the brought warmth turns into mechanical work. For comparable addition of q_{br} and l_{com} it is expedient to accept that the auxiliary heat engine located in the environment is used to implementation of compression of a working body. Operation of such engine is also modeled by means of a

direct cycle. In this cycle warmth q'_{br} is failed to a working body, work of expansion l'_{ex} and compression l'_{com} of a working body are made. Thus, work of l_{com} in an initial direct cycle is made, generally, at the expense of a part of operation l'_{ex} of the auxiliary engine. The total costs of warmth of 1 J/kg of work l'_{ex} in the auxiliary engine make:

$$\Delta = \frac{q'_{br} + l'_{com} \cdot \Delta'}{l'_{ex}}, \quad (3)$$

where Δ and Δ' – is the total costs of specific heat in cycles on 1 J/kg of specific works of l_{com} and l'_{com} respectively.

Due to introduction to (3) sizes Δ' the nonequivalence of warmth q'_{br} and work l'_{com} at their addition is considered.

As a result the general expression for the coefficient considering all costs of realization of direct circular process, Ku takes a form:

$$Ku = \frac{l_{ex}}{q_{br} + l_{com} \cdot \left(\frac{q'_{br} + l'_{com} \cdot \Delta'}{l'_{br}} \right)}. \quad (4)$$

Strictly speaking, by drawing up thermodynamic models of operation of power stations for the general case, size Δ and Δ' are not equal. For the analysis of

properties of criterion of Ku will let's assume their equality. Let's also in addition accept that the following sizes are equal among themselves: $q_{br} = q'_{br}$, $l_{com} = l'_{com}$, $l_{ex} = l'_{ex}$. As a result of it (3) it is possible to write down in a look:

$$\Delta = \frac{q_{br} + l_{com} \cdot \Delta}{l_{ex}} \quad (5)$$

From (5) we receive:

$$\Delta = \frac{q_{br}}{l_{ex} - l_{com}} \quad (6)$$

Substituting (6) in (4) for the considered special case providing a number of the assumptions described above, we receive expression:

$$\begin{aligned} Ku^{AS} &= \frac{l_{ex}}{q_{br} + l_{com} \cdot \frac{q_{br}}{(l_{ex} - l_{com})}} = \\ &= \frac{l_{ex} - l_{com}}{q_{br}} = \frac{l_{cyc}}{q_{br}} = \eta_t \end{aligned} \quad (7)$$

where Ku^{AS} – value of criterion Ku at the assumptions made for the considered special case.

From (7) follows that at the assumptions made upon transition from the general to the particular to the case considered above the coefficient considering all expenses becomes equal to the thermal coefficient useful action of a direct cycle which can be determined by a formula:

$$\eta_t = \frac{l_{ex}}{q_{br} + l_{com} \cdot \frac{q_{br}}{(l_{ex} - l_{com})}} \quad (8)$$

From (8) follows that when determining thermal coefficient useful action of a direct cycle, as useful effect work expansion of a working body of l_{ex} , and as expenses the sum of all types of the energy brought for realization of a cycle in a comparable form can be taken over. And by such comparison it is assumed that for 1 J/kg of work of l_{com} it is spent as much warmth, how many for 1 J/kg of work of all cycle l_{cyc} . It should be noted that without consideration of logic of transition from the general case (4) to private (7), the last assumption cannot be considered as strictly reasonable.

For the specific conditions which are found in various HTI, expression for criterion of Ku can take a different form [16]. For a reversible cycle by means of which work of steam-power installation is modeled work of a cycle, as we know, can be determined by formula:

$$l_{cyc}^{SPI} = l_{tur} - l_{pu} \quad (9)$$

where l_{cec}^{SPI} – specific work of a cycle of steam-power installation, J/kg; l_{tur} and l_{pu} – specific theoretical technical operation of the turbine and the pump providing the required pressure of feed water, J/kg.

Proceeding from (9), when determining for steam-power installation of criterion of efficiency for the general case on type (4), as useful effect technical work the turbine l_{tur} , and as all expenses – the sum of the warmth brought in a cycle to a working body q_{br}^{SPI} and the technical work of l_{pu} spent during the operation of the pump, in a comparable form is taken over:

$$Ku^{SPI} = \frac{l_{tur}}{q_{br}^{SPI} + l_{pu} \cdot \Delta^{pu}} \quad (10)$$

where Ku^{SPI} – is the effectiveness ratio considering all main costs of energy of implementation of a reversible cycle of steam-power installation; Δ^{pu} – the total costs of specific heat in a cycle falling on 1 J/kg of specific operation of the pump l_{pu} .

Quantity Δ^{pu} , by analogy with (3), is on a formula:

$$\Delta^{pu} = \frac{q_{br}^{SPI} + l'_{com}^{pu} \cdot \Delta'_{pu}}{l'_{ex}^{pu}} \quad (11)$$

where q_{br}^{SPI} – the specific heat brought to a working body in the cycle modeling operation of the auxiliary engine ensuring functioning of the pump, J/kg; l'_{com}^{pu} and l'_{ex}^{pu} – specific works of compression and expansion of a working body in a cycle of the auxiliary engine, J/kg; Δ'_{pu} – the total costs of specific heat in a cycle of the auxiliary heat engine falling on 1 J/kg of specific work l'_{com}^{pu} .

Having accepted as assumptions the additional conditions similar to considered above about what $q_{br}^{SPI} = q'_{br}^{SPI}$, $l_{pu} = l'_{com}^{pu}$, $l_{tur} = l'_{ex}^{pu}$, $\Delta^{pu} = \Delta'_{pu}$, from the expressions (10) and (11) defining criterion of Ku^{SPI} for the general case it is possible to receive for this special case:

$$\begin{aligned} Ku^{SPIAS} &= \frac{l_{tur}}{q_{br}^{SPI} + l_{pu} \cdot \frac{q_{br}^{SPI}}{(l_{tur} - l_{pu})}} = \\ &= \frac{l_{tur}}{q_{br}^{SPI} + l_{pu} \cdot \frac{1}{\eta_t^{SPI}}} = \eta_t^{SPI} \end{aligned} \quad (12)$$

where Ku^{SPIAS} – criterion of Ku^{SPI} at the accepted assumptions; η_t^{SPI} – thermal efficiency of steam-power installation.

Equation (12) shows that in the considered above particular case, the thermal coefficient useful action of steam power plant will be equal to the criterion for Ku , taking into account all comparable energy costs for the implementation cycle plants.

Let us consider the practical application of the Ku criterion by comparing the performance of a steam power plant on two different cycles in the same temperature range: the Renkin cycle on saturated steam and the Carno cycle on saturated steam. It is known that if we evaluate the efficiency of these cycles using thermal efficiency, the Carno cycle is more effective. At realization of such cycle of Carno mechanical energy in the quantity corresponding about 55% of the turbine energy is spent for the drive of the compressor [17, 18]. It can be shown that when evaluating the effectiveness of these cycles using the Ku criterion, the opposite result is obtained.

Let's accept for assessment the temperature range in which cycles from 25 to 350 °C are implemented, we will consider Operation of the turbine l_{tur} in both cycles identical. A condition of the preference of a cycle of Renkin's over Carno's cycle written as:

$$Ku^R > Ku^C, \quad (13)$$

where Ku^R and Ku^C – the coefficients considering everything the costs of realization of cycles in a comparable form calculated for Renkin's and Carno's cycle, respectively.

From (13), taking into account (10), it turns out:

$$q_{br}^R + l_{pu}^R \cdot \Delta^R < q_{br}^C + l_c^C \cdot \Delta^C, \quad (14)$$

where q_{br}^R and q_{br}^C – the specific warmth brought to a working body in Renkin's and Carno's cycles, respectively, J/kg; l_{pu}^R – specific operation of the pump in Renkin's cycle, J/kg; l_c^C – specific operation of the compressor in Carno's cycle, J/kg; Δ^R and Δ^C – the total costs of specific heat in cycles falling on 1 J/kg, specific operation of the pump l_{pu}^R (in Renkin's cycle) and the compressor l_c^C (in Carno's cycle).

When determining sizes Δ^R and Δ^C it is also considered that the pump in Renkin's cycle has the coefficient useful action – η_{pu} , and the compressor in Carno's cycle has the coefficient useful action – η_c .

Operation of drives at the pump and the compressor is carried out at the expense of the electric energy brought to them which is developed, for example, on the turbine plant with absolute electric coefficient useful action η_{TPE} . As a result we receive:

$$\Delta^R = \frac{1}{\eta_{pu}} \cdot \frac{1}{\eta_{TPE}} \quad \Delta^C = \frac{1}{\eta_c} \cdot \frac{1}{\eta_{TPE}} \quad (15)$$

For confirmation of justice of inequality (14) we will carry out its assessment. For assessment it is possible to accept that $\eta_{pu} = \eta_c = 1$; $\eta_{TPE} = 0,4$; $l_c^C = 0,5 l_{tur}$; $l_{pu}^R = 0,1 l_{tur}$. As a result from (14) we receive:

$$q_{br}^R - q_{br}^C < l_{tur}. \quad (16)$$

In the considered range the thermal coefficient useful action of a cycle of Carnot η_t^C will is equal 0,52, therefore, we can write down:

$$\eta_t^{SPI} = \frac{l_{cyc}^C}{q_{br}^C} \cdot \frac{q_{br}^C - q_{re}^C}{q_{br}^C} = \frac{l_{tur} - l_c^C}{q_{br}^C} = 0,52, \quad (17)$$

where q_{re}^C – the specific taken-away heat in Carno's cycle, J/kg.

Taking into account the assumptions made above from (17) we receive:

$$l_{tur} = 1,04 \cdot q_{br}^C. \quad (18)$$

Substituting (18) in (16) we receive:

$$q_{br}^R < 2,04 \cdot q_{br}^C. \quad (19)$$

It is easy to be convinced that inequality (19) is carried out.

4 Discussion

Comparison of efficiency of cycles on criterion of Ku shows that Carno's cycle in this case is less preferable not only because the compressor for compression of the wet vapor having large specific volume is the bulky construction difficult in terms of operation, but also because taking into account all power expenses it is less favorable.

Thus, transition in work of steam-power installations from Carno's cycle on saturated steam on Renkin's cycle on saturated steam, when using criterion of Ku , become more reasonable.

The possibility of increase in validity of the choice of rational technical solutions in the field of the heat power equipment increases, eventually, overall effectiveness of use of different types of fuel [19, 20]. And it, in turn, leads to decrease in specific values of harmful emissions in many technological processes on a number of indicators [21], ensuring a reduction of environmental pressures on the environment [22, 23, 24]. Thus:

1. For expansion of opportunities when carrying out thermodynamic estimates of efficiency of heat power installations the new criterion of Ku considering as

expenses different types of the energy brought to a working body in a comparable form is offered.

2. A certain connection between the offered criterion of K_u and thermal coefficient useful action of a direct cycle η_t is established.

3. Increase in validity of the choice of technical solutions cuts volumes of fuel consumption and provides environmental friendliness of processes due to reducing of contamination, including the thermal one [25].

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