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Effects of the water injection into the hot charge at isochoric conditions

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ABSTRACT

The significant growth of the IC engine efficiency can be achieved among others by the diminishing of the charge exchange work and as well by arranging of the energy recovery in the engine system. The issue of the 6-stroke (3-revolution) cycle and its implementation in the entire IC piston engine cycle should be considered as an important proposal in this field of research. Increase of the energy efficiency occurs especially meaningful within the range of part load of IC engine. The internal energy of the combustion products from the first stage is trapped in the system and next effective used in the second added stage of the modified cycle. The characteristic element of the 6-stroke cycle is the liquid water injection into the charge captured in the engine cylinder, but the point of the water injection should be very attentively determined.

1. Introduction – object of interest

Conversion of chemical energy of fossil fuels, using various systems of heat engines (including internal combustion engines) is today the dominant way of obtaining the mechanical work (pure exergy). Improvement of systems used, primarily in the context of further growth of their energy efficiency is still a major research problem in this regard. The issue of 6-stroke (3-revolution) cycle of the internal combustion piston engine – mainly advisability of the application in real systems, its structure and components, parameters of thermodynamic processes and the organization and implementation of the entire cycle – can be considered as an important proposal in this field of research.

Recently while making a systematic review of the literature in the field of interest issues of 6-stroke engine cycle we came across, among others. The publication of the authors:

James C. **Conklin**, James P. **Szybist**: "A highly efficient six-stroke combustion engine cycle with water injection for in-cylinder exhaust heat recovery". **Energy** 35 (2010) pp. 1658–1664.

After reading the contents of this publication, we noticed that the 6-stroke cycle aforementioned by authors (JC Conklin, JP Szybist) differs significantly from the 6-stroke engine eco-cycle proposed and presented by us [1–3].

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The main idea presented by the authors (JC Conklin, JP Szybist) is included in the description of the added part of the cycle (*Energy 35, p. 1659*):

> "The modified cycle proposed here adds two additional strokes that increase the work extracted per unit input of fuel energy. These additional strokes involve trapping and recompression of some of the exhaust from the fourth piston stroke, followed by a water injection and expansion of the resulting steam/exhaust mixture. The residual exhaust gas is trapped in the cylinder by closing the exhaust valve earlier than usual, i.e. well before the top center (TC). Energy from the trapped recompressed exhaust gases is transferred to the liquid water, causing it to vaporize and **increase the pressure**. This added pressure then produces more work from another expansion process."

Unfortunately, with such a formulation of given idea we can not agree, because this concept of a 6-stroke cycle – in our opinion – is wrong.

We argue that the injection of liquid water into the adiabatic chamber previously filled with hot gas (e.g. exhaust), by keeping constant volume (isochoric process, V = idem) of the system – will not result in an increase of the pressure (charge of the water vapor_fumes) within the chamber, but on the contrary – mainly occurs a pressure drop ($dp < 0$) of the charge in the chamber.

As consequence of this pressure drop ($dp < 0$), the added part of the engine cycle will be always left-running and following this the work performed in this part of the cycle must be negative.

The explanations together with the reasons given above insights are presented in the point 2.

Then additional, at point 3 of his article, the another (independent of the former proprietary solutions) solution is proposed, which includes the direct injection of liquid water into the hot charge in the engine cylinder and it can be implemented as element of 6-stroke engine cycle.

Such a modified realization of the 6-stroke engine cycle should ultimately lead to an increase in effective work of the whole cycle and then finally will improve its energy efficiency.

2. Justification of the indicated objections; parameters of the charge after water injection

A simplified scheme of the analyzed system, with a direct injection of liquid water into the hot exhaust charge, remaining in isochoric-adiathermic conditions in the engine cylinder, is shown in Fig. 1.

Instantaneous energy balance of the system (Fig. 1) for the step of the liquid water injection:

$$h_w \cdot dm_w = d(m \cdot u) \quad (1)$$

whereby: h_w – specific enthalpy of the injected liquid water, kJ/kg,

dm_w – differential mass of the injected water, whereby: $dm_w > 0$, kg,
m – instantaneous mass of the charge in the cylinder, kg,
u – specific internal energy of the exhaust charge, kJ/kg.

The specific enthalpy h_w of the injected liquid water equals:

$$h_w = -h_{ev} \quad (2)$$

where: h_{ev} – enthalpy of the water evaporation; it equals about: $h_{ev} \approx 2240$ kJ/kg, and additionally from substance balance results:

$$dm = dm_w. \quad (3)$$

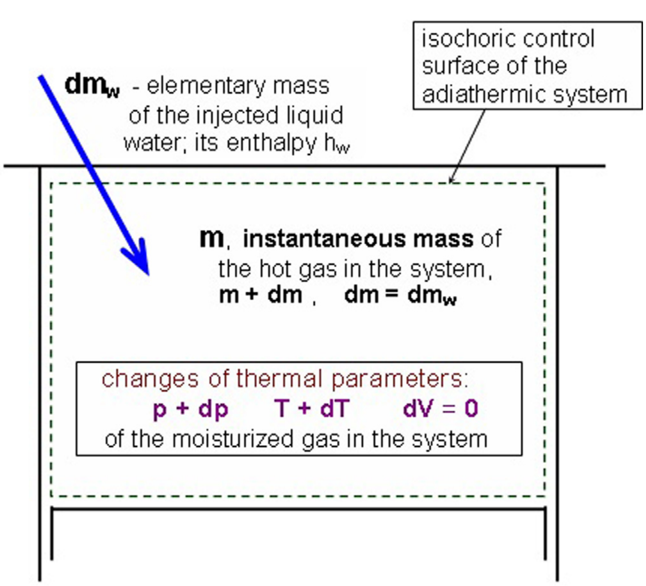

Fig. 1. Scheme of the analyzed isochoric-adiathermic system.

The energy balance is set by taken the state of the saturated water vapor as the reference state, so the enthalpy of the liquid water is negative. Equations (1)–(3) after a simple transformation take the form:

$$m \cdot du = -(h_{ev} + u) \cdot dm \quad (4)$$

Since the expressions: $[-(h_{ev} + u)] < 0$ and simultaneous: $dm > 0$ thus, from equation (4) the relation: $\mathbf{du < 0}$ implies, and thereby $\mathbf{dT < 0}$ because $du \approx c_v \cdot dT$,where: T – the instantaneous temperature of the whole charge, K,

c_v – specific heat capacity of the charge, kJ/(kg · K).

Injection of liquid water portion into the hot charge will ultimately result in a decrease in of its temperature ($dT < 0$) in the isochoric-adiathermic system.

To estimate the instantaneous pressure change dp in the system, should be used the thermal state equation of the substance contained in the system; in this case it can be the Clapeyron equation in the form:

$$p \cdot V = m \cdot R \cdot T \quad (5)$$

where: R – individual gas constant, $R = (\kappa - 1) \cdot c_v$, kJ/(kg · K),

κ – ratio of the specific heat capacities, $\kappa = c_p/c_v$.

After differentiating the equation (5) at the condition: $dV = 0$, will be achieved:

$$V \cdot dp = R \cdot d(m \cdot T) \quad (6)$$

and:

$$V \cdot dp = (\kappa - 1) \cdot d(m \cdot c_v \cdot T), \quad \text{next}: \quad V \cdot dp = (\kappa - 1) \cdot d(m \cdot u), \quad (7)$$

hence, taking into account equations (1)–(3) is obtained:

$$V \cdot dp = -(\kappa - 1) \cdot h_{ev} \cdot dm. \quad (8)$$

From equation (8) follows the relationship:

$$dp = -\frac{(\kappa - 1)}{V} \cdot h_{ev} \cdot dm, \quad (9)$$

and because: $dm > 0$ therefore also finally: $\mathbf{dp < 0}$.

In this context, since – as indicated above – the injection of liquid water into the charge, in addition to the decrease in temperature ($\mathbf{dT < 0}$) **occurs pressure drop** ($\mathbf{dp < 0}$) of the charge contained in the system, and so the added part of the engine cycle proposed by authors (JC Conklin, JP Szybist) – will be always left-running and following this the work performed in this part of the cycle must be negative.

As a result will be finally obtained the reducing of the total work achieved within the proposed 6-stroke engine cycle. This will result in a reduction in the overall energy efficiency of the engine cycle, and therefore the expected positive effects do not occur.

3. Modified system with direct liquid water injection into the engine cylinder

The scheme of the modified (independent of the former proprietary solutions) solution, which includes the direct injection of liquid water into the hot charge in the engine cylinder is shown in Fig. 2. This solution can be implemented as element of 6-stroke engine cycle.

In this case analyzed system contains an additional solid insert, its mass equals m_s, kg, with earlier accumulated energy Q_s, which can be systematically transferred (as: $dQ_s = m_s \cdot c_s \cdot dT_s$) into the