Simulation of the Centrifugal Compressor Flow Part of the Internal Combustion Engine to Determine Areas of Non-Evaporated Moisture Effective Discharge during Charge Air Evaporative Cooling

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Abstract. The article presents the results of modeling the operating parameters of an engine pressurization assembly centrifugal compressor at evaporative air cooling. A step-by-step method for calculating a centrifugal compressor is described in order to evaluate the effect of evaporative cooling and air humidity on the temperature behind a centrifugal compressor. The proposed method for calculating the operating parameters of an engine pressurization assembly centrifugal compressor of an internal combustion engine with evaporative air cooling is used to evaluate the effect of humidity on the operation of a turbo compressor using an author program (certificate of state registration of the computer program № 2016611761). A series of calculations of a centrifugal compressor parameters was carried out with finely dispersed water in front of the compressor, which allowed the air humidity to be maintained at 100% with changes in temperature and pressure during the compression process. Analysis of the results showed areas in which it is advisable to organize the separation and removal of excess moisture. The presented research results are necessary for choosing the methods for separating moisture during evaporative cooling of charge air in turbocharged internal combustion engines.

1. Introduction

Forcing diesel engines according to the average effective pressure and at a nominal frequency of rotation of the crankshaft results in a significant reduction in weight and size of internal combustion engine, with growth of the temperature, absolute and relative dimensions of its particularly coolers [4, 6, 11].

To reduce the thermal stress in engines with supercharging, a combination of recuperative air cooling with the Miller method is used, consisting in the expansion of air in the cylinder at the end of the intake stroke due to the early closing of the intake valve [11].

2. Main part

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When using a two-stage supercharger that significantly complicates the design of the air supply system, one of the effective ways to reduce the charge air temperature can be evaporative cooling, in which injection of 1% of water reduces the air temperature by 25 °C [6,7,11]. However, the advantage in the power and efficiency of the ICE is reduced due to the need to compress the formed water vapor and additional losses due to the disruption of the kinematics of the air flow, the need to transport droplets and water films along the surfaces of the flowing part of the centrifugal compressor.

For forcing ICE, an essential characteristic affecting the quality of the workflow and power is density. Therefore, to control the upper temperature point when compressing a working fluid in a centrifugal compressor commonly used a fine mixture of liquid, such as water, which will allow, when the fluid supply volume is correctly selected, to lower the outlet temperature to the boiling point, which is several times lower than the normal gas temperature at the centrifugal outlet compressor.

Many studies have been conducted confirming the effectiveness of evaporative cooling in turbo-compressors of internal combustion engines (ICE). For example, the British Research Association for the internal combustion engine obtained the following results of studies of the efficiency of cooling the charge air by injecting water into the compressor inlet: the charge air temperature decreased by 19.5 °C, which reduced the power consumed by the compressor by 2.5% and contributed to an increase in air mass flow by 4%; when the water consumption for evaporative cooling is doubled, the mass supply of the compressor (at the same power) increased by 8%, and the charge air temperature decreased by 51 °C.

One of the problems with the use of evaporative cooling is the lack of calculation methods and mathematical models that describe in aggregate the processes that occur during the compression of two-phase flows with a fine suspension of the liquid phase in a compressible gas, thermodynamic processes and phase transitions. In addition, it is necessary to take into account the processes of conglomeration and crushing of the liquid phase elements. In a centrifugal compressor, separation and sedimentation in the form of moisture films on compressor elements, followed by their crushing and disruption, also takes place, which also requires the development of mathematical models and the calculation and analysis of ongoing processes.

Known calculation methods involve finding the peripheral speed (for a certain degree of pressure increase) or finding the degree of pressure increase at a given peripheral speed [1, 4]. The disadvantage of modern thermogasdynamic calculation methods of a single-stage supercharger is the lack of consideration of the liquid phase and, as a consequence, phase transitions, as well as a small degree of detail that does not allow to properly calculate, analyze the processes that occur during evaporative cooling and choose the most effective ways to remove liquid and moisture from the air. elements of the compressor, cooler and intake manifold of the internal combustion engine.

Therefore, in this paper, we consider the effect of evaporative cooling of charge air and the change in air humidity on the operation of a single-stage compressor of a pressurization unit, and an assessment was made of the possibility of separating unevaporated or condensed moisture in the flowing part of the compressor and beyond.

Parameters of the compressor are calculated in 6 sections: 0 (initial) - inlet to the impeller, 1 - input to the blade grid, 2 - exit from the impeller, 3 - inlet to the diffuser, 4 - entrance to the cochlea, 5 (final) - exit from the cochlea.

To take into account the influence of air humidity and evaporative cooling of the charge air in each section, the change in the calculated parameters from the characteristics of the compressed gas was analyzed. The characteristics of the compressible body change as follows: moisture content, gas constant, isentropic index, and compressibility factor of moist air.

Calculation of the turbocharger was carried out in several stages along six sections [7, 10] (see Figure 1).
Figure 1. Calculation scheme of the centrifugal compressor flowing part.

1. At the first stage, the parameters of the compressible gas were calculated: the gas constant (R), the moisture fraction (x), the isentropic index of the compressible gas (k) and the compressibility factor (z).

2. At the second stage (when calculating the parameters of the flow part), calculated:
   - Gas compression by sections;
   - Gas flow exit angle in the absolute motion of the impeller (α₂);
   - Mach numbers at the peripheral speed and actual;
   - The temperature of the gas at the outlet of the impeller (T₂);
   - Absolute speed at the outlet of the impeller; and etc.

3. At the third stage, the parameters of the impeller along the sections were calculated: gas velocity (c₀); gas density at the compressor inlet (ρ₀); gas temperature (ΔTₙ₀); gas compression (ε₀), (ε₁), (ε₂); density and gas pressure (ρ₀ and p₀), (ρ₁ and p₁), (ρ₂ and p₂); absolute velocity of the gas (c₁); gas flow entry angle in relative motion to the wheel blades (β₁); relative velocity of the gas (w₁); gas temperature (T₁); Mach number in relative velocity (Mw₁); temperature of the gas at the outlet of the impeller (ΔTₙ₂);

4. Further, the parameters of the bladder diffuser were calculated. The following characteristics were calculated: the gas flow entry angle (α₃=α₂); gas velocity (C₃), (C₄); gas temperature (T₃), (T₄); gas compression (ε₃), (ε₄); gas density and pressure (ρ₃ and p₃); gas density and pressure (ρ₄ and p₄); the average value of the angle α in the path of the gas in the diffuser (αₙ);

5. The parameters of the inner cochlea were calculated: the twist of the flow at the exit from the diffuser (Cₙ); radius of the inner surface of the cochlea Rₙ.

6. At the sixth stage, the gas parameters were calculated in the final (outlet) section of K-K: the gas temperature in the final section of K-K (Tₚ); gas compression in the final section (εₚ); density and gas pressure in the final section (ρₚ and pₚ).

To evaluate the efficiency, the following characteristics were calculated: the compression power of the gas in the polytropic process in the compressor (internal compressor power) (Nₚ); Capacity of gas compression in an isentropic process (Nₗ); The compressive power of the gas in the isothermal process (Nᵢ); Isentropic internal efficiency (ηᵢ); Isothermal internal efficiency (ηᵢ).
Calculation of a turbocharger that produced using computer programs written in C++ is designed to calculate the main parameters of the centrifugal compressor flow section geometry [9].

After clicking the “Calculate” button, the intermediate characteristics are calculated and displayed on the screen, both formulas and calculation results. At the same time, pressing the «Open images» button allows you to see the compressor sections.

3. Conclusion
To assess the effect of humidity on the operation of the turbocharger, a series of computations of the parameters of the centrifugal compressor was carried out at the following humidity values: 0, 20, 60, 100%, and also with fine dispersion of water in front of the compressor, which allowed to maintain the humidity at 100% with changes of temperature and pressure in the process of compression.

An analysis of the results obtained showed areas in which it is advisable to organize separation and removal of excess moisture [5, 12].

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