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Numeryczno-eksperymentalne badania zjawiska chłodzenia termoakustycznego

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The dissertation concerns the analysis of the effects of a thermoacoustic device with its design features and operational parameters changed in a wide range. The main purpose of the research was to determine the dependence of the operating parameters of a compact thermoacoustic cooler on its features and the working environment, as well as to determine its particularly favorable design features.

As part of the research, various methods of computational analysis of this type of devices were used, taking into account the study of one- and three-dimensional models. The results of the numerical tests were compared to the results of complex experimental tests carried out on a dedicated test stand.

One of the most frequently used tools dedicated to numerical analysis of thermo-acoustic devices is the DeltaEC software, the essence of which is based on the numerical solution of equations for a one-dimensional model. This software is characterized by a number of features that both enable its wide application (e.g. short time of calculations) and require the assessment of the expected process parameters before starting the tests (e.g. limiting the permissible parameters of the acoustic wave). For this reason, the paper discusses the theoretical basis of the computational process implemented in the application and highlights simplifications potentially particularly important for the analysis of compact devices. The methodology of developing a compact thermo-acoustic device model is presented, taking into account the characteristics of the sub-models available in the computing platform used. A model of a compact thermo-acoustic device was developed, taking into account the variation of geometric, material and environmental parameters analogous to the one assumed at further stages of the works. Then, using the prepared model, a parametric analysis was carried out.

In the next stage of model research, Ansys CFX computational fluid dynamics (CFD) software was used. The use of CFD tools is a common practice in the numerical analysis of thermoaxutic devices, due to the possibility of mapping local phenomena, which gives the chance to obtain results significantly similar to the actual operating parameters of the devices. However, the application of this method is often burdened with the difficulty in the form of significant simulation time, which is a fundamental limitation in its widespread use. The paper presents the proposed methodology of preparing a model of a thermo-acoustic device, with particular emphasis on the selection of sub-models available in a selected computing environment. The essence of model verification and validation is discussed, both in the context of the analysis of the sensitivity of the results to inherent model parameters and the comparison of the results of preliminary analyzes with the literature. At this stage of the research, a set of three-dimensional models of a thermo-acoustic device was prepared, with a set of geometric features similar to the features of the system used in the experimental research. Then, this set was analyzed by changing the material and environmental parameters.

Due to the significant computational cost of numerical tests carried out with the use of CFD tools, their use in broad parametric analyzes is limited. In addition, the development of a model appropriate for this type of analysis requires its validation based on measurement data. Similarly, due to the significant simplifications in the mathematical description of the thermoacoustic phenomenon implemented in the set of equations to be solved, the widespread use of the DeltaEC application seems unjustified. For this reason, it was decided to conduct reference experimental studies. These tests included measurements on a dedicated test stand for all sets of constructional features and environmental parameters analyzed during the numerical tests. In order to reduce the time necessary to carry out the works, the selection of sets of design features and device parameters used in the numerical analysis was based on an adequate experimental design.

At this stage, the selection of the experimental design appropriate for the assumed number of changed parameters and their value levels was discussed. The design premises of the compact cooling device, which is part of the stand, were presented, as well as the key aspects of measuring lines and control devices at the stand. The essence of the selection and calibration of the sensors used as well as the basis for the automation of measurements were also marked. The used experimental stand was presented, and the influence of the parameters of its most important elements on the possibility of observing the thermoacoustic phenomenon was discussed. The measurement procedure and the methodology of identifying the acoustic parameters of the tested device with the use of selected mathematical processing and signal analysis tools were also discussed.

In the last stage of the work, the procedure for estimating the occurrence of gross errors in the obtained experimental results and the methodology for estimating measurement errors were discussed. The methodology of presenting the results of experimental research was also presented.

The results of numerical research using both one- and three-dimensional analyzes were presented and discussed. The results of experimental research with estimated values of measurement errors are also presented.

The performed analyzes showed a satisfactory convergence of the CFD simulation results with the experimental data, taking into account the estimated measurement errors. The fundamental influence of the geometry of the regenerative exchanger and the working gas pressure on the observed temperature difference inside the thermo-acoustic device was revealed. It was found that there is a range of parameter values describing the geometrical features of a compact device for which the maximum values of the temperature difference inside it are observed. It has been shown that this range is only slightly dependent on the environmental parameters of the device.

Moreover, the possibility of using the DeltaEC software to determine the general dependencies of operational parameters on design features and environmental parameters was demonstrated. The collected data showed a satisfactory agreement with the observed experimental data in terms of the trend of the analyzed operating parameters, taking into account the elimination of gross errors. At the same time, a limited use of the selected platform was demonstrated for conducting parametric analyzes in a wide range of input data variability due to the risk of latent calculation errors.

The results of the numerical tests carried out in the CFD environment showed a satisfactory compliance of the results with the results of the experiment, taking into account the estimated measurement errors. The simulation results show that the operating parameters of the device depend on its geometrical features and, to a lesser extent, the type and pressure of the operating gas used. Moreover, the simulations carried out showed the existence of a risk of a breakdown of the thermo-acoustic phenomenon for devices characterized by unfavorable geometrical features of the regenerative exchanger.

The results of the conducted research allowed to identify the influence of design features and environmental parameters on the operational parameters of a compact thermo-acoustic cooler. The collected data also made it possible to identify particularly advantageous features of such a device.