Closure to "Discussion: 'Design Improvements to a Biomass Stirling Engine Using Mathematical Analysis and 3D CFD Modeling' " (2007, ASME J. Energy Resour. Technol., 129, pp. 278, 279, 280)

K. Mahkamov
School of Engineering,
Durham University,
Durham, DH1 3LE, UK
e-mail: khamid.mahkamov@durham.ac.uk

First, the current author would like to thank everyone who provided comments in Refs. [1–3] regarding the results published in Ref. [4]. The aim of the paper was to demonstrate capabilities of the 3D Computational Fluid Dynamics (CFD) technique for modelling a Stirling engine.

Questions arising and answers can be grouped into the following points.

Soundness of the original design. From the comments made in Refs. [1–3], the authors believe that "soundness" of the original design was lost during the transformation into the alpha machine, together with the fact that the original engine could have improved its performance above that of the modified machine if an error with the piston's crown had been eliminated.

In addition to the "the gas entrapment" problem, the original engine had also the following shortcomings:

- the heater tubes blocked each other from contact with the hot combustion products,
- the engine had an excessive dead volume,
- there were high axial heat conduction losses in the regenerator, and
- the engine had unreliable shaft seals.

Shaft seals used make it difficult to achieve the required level of sealing. This applies even in cases when the working fluid is a "heavy" gas (air or nitrogen). The main reason is that the seal has a relatively large diameter and this introduces unavoidable inaccuracies in the shape and surface of the counterpart component during the manufacturing.

I fully agree with the comment in Ref. [1] that engine design involves more than just simply thermodynamics and fluid flow. Designing an engine is a complex procedure that requires finding the correct balance between conflicting requirements. The conversion of the gamma configuration into the alpha layout increases the load on the displacer rings and on the shaft, resulting in an increase of mechanical losses and a reduction in the lifetime of rings. However, in this particular case, there were only two options available.

The first option was that the engine would remain as a gamma machine, hence able to exert a little power, but equipped with displacer rings possessing a longer service period while the second option was to employ the proposed alpha configuration with the loads on the displacer rings approximately equal to that of the power piston. The cost of a set of displacer rings is a very small fraction of the engine's cost and, in addition, the alpha design completely eliminates the displacer rod sealing.

The displacer ring issue has never been considered as a defining factor in choosing an engine's layout. Many successful Stirling engines with satisfactory service intervals have the alpha layout.

Elimination of entrapment of the working fluid by the power piston's crown. Durham University provided a solution which involved minor changes to the existing design. Other changers in the gamma machine, potentially "eradicating the entrapment problem," would increase the dead volume to a critical value and therefore these were not modeled using the computationally expensive CFD technique. However, a comparison of performance of the alpha and gamma engines with the same regenerator and cooler porosities was performed with the application of the second-order mathematical model (MM). These calculations demonstrated that the alpha machine had higher power output because of its smaller overall dead volume and lower hydraulic losses. Moreover, although the author of Ref. [2] states that the gamma design would be more efficient than the new modified engine, he acknowledges that its power output was greater by a factor of 2 even at the lower charging pressure.

The Bill number referred to in Ref. [3] is a parameter that is used for very preliminary estimates with back-of-the-envelope calculations and does not consider design features of engines. Thus, this "goodness" parameter has a very limited practical value.

Use of the term biaxial asymmetric motions of pistons and its calculation. The term "biaxial asymmetric motions of pistons" was used by the company in all their correspondence with the current author and the company supplied the equations for the calculations of piston displacements in "biaxial asymmetric" mode. Calculations show that when the conrod to the piston stroke ratio is greater than 1.13, then the "biaxisymmetric" displacement and harmonic curves, indeed, coincide. However, the developed second-order and CFD models are capable of incorporating displacements of any character.

Constant changing of nomenclature. The comment was raised in Ref. [1] about "the constant changing of the nomenclature." The author in Ref. [1] is assuming that for each result obtained using the second-order MM, there are equivalent data from the 3D CFD modeling. The latter provides more detailed information on the working process. To avoid any confusion in the interpretation of the results, each diagram includes its own caption, clearly explaining the corresponding symbols being used.

It is established practice to present two pressure-volume diagrams for any type of Stirling engines when the second-order MM is employed since it produces an identical pressure for both parts of the compression space. However, 3D CFD modeling provides pressure curves for the two parts of the compression space, which differ greatly due to entrapment effects.

Design of the cooler. Some inaccuracies in the description of the design parameters of the cooler were correctly highlighted. The engine's six annular cylindrical coolers house 9720 cooler slots overall and the correct data were used in the simulations. In the 3D CFD model, each cooler's cylinder was presented as a porous medium to avoid an unacceptably large computational grid. Therefore, the cross section form of individual channels did not play any role in the CFD calculations.

Accuracy of computational results and comparison with experimental results. Results of the experimental performance of the engine were not published since these were solely the property of the company undertaking the research. The author of Ref. [2] was not a part of this research but states that computational results obtained bear little resemblance to those obtained testing the real engine. The conditions under which tests, referred in Ref. [2], were run are uncertain, since the engine was not instrumented with pressure or temperature sensors, and there is no information about the temperature on the surface and of the working fluid in the heat exchangers. The engine seals could not prevent the continuous leakage of the working fluid and this would make the test conditions even more vague.

The accuracy of CFD modeling depends on the correctness of

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input data, which was not available in the modeling process. During the investigations, information on the heat fluxes was unknown and therefore several cases were numerically investigated. The results of the power output presented in Ref. [4] were obtained for the case when the heat flux level was its lowest. Results of the CFD simulations show that for a medium heat flux, the indicated power from the engine is about 4.8 kW. This value is considerably higher when the highest heat flux value is applied and the company was fully satisfied with theoretical results obtained.

Additionally, theoretical results from CFD modeling have been verified against experimental data obtained using a Stirling engine of the in-house design at Durham University, which was equipped with instantaneous pressure and temperature sensors.

References

[1] Burton, R., 2007, "Discussion: 'Design Improvements to a Biomass Stirling Engine Using Mathematical Analysis and 3D CFD Modeling,' (Mahkamov, K., 2006, ASME J. Energy Resour. Technol. **128**, pp. 203–215)," ASME J. Energy Resour. Technol., **129**, pp. 278.

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[3] Burton, J. D., "Discussion: 'Design Improvements to a Biomass Stirling Engine Using Mathematical Analysis and 3D CFD Modeling,' (Mahkamov, K., 2006, ASME J. Energy Resour. Technol. **128**, pp. 203–215)," ASME J. Energy Resour. Technol., **129**, pp. 280.

[4] Mahkamov, K., 2006, "Design Improvements to a Biomass Stirling Engine Using Mathematical Analysis and 3-D CFD Modeling," ASME J. Energy Resour. Technol., **128**, pp. 203–215.