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A prediction of the acoustical properties of induction cookers based on an FVM–LES-acoustic analogy method

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ABSTRACT

The FVM–LES-acoustic analogy method (FVM–LES-AAM), which is a hybrid prediction technique for the acoustical property computation, is presented and performed in this paper. The FVM–LES-AAM was developed by combining the finite volume method (FVM), the large eddy simulation (LES), and the Ffowcs Williams-Hawkings analogy algorithm (FWH-AA). To predict the acoustical properties of induction cookers, the FVM is used for discretizing the calculation field and building numerical equations, and the LES and FWH-AA are performed for computing the sound sources and predicting the far-field sound, respectively. Using the FVM with the unstructured grids method to discretize the control equation of Navier–Stokes was introduced for illuminating the above numerical simulation procedure. To prove the FVM–LES-AAM method is feasible for predicting the acoustical property of induction cookers, the simulated results were compared with some measured experimental data. The comparisons suggest that the hybrid method is accurate and reliable for the aeroacoustics analysis of induction cookers. Considering the temperature performance, furthermore, some new configurations for the noise reduction of induction cookers were designed, simulated, and discussed. The FVM–LES-AAM prediction technique shows promise as a feasible and computationally affordable approach for not only noise analysis of induction cookers, but also for other aeroacoustics problems in engineering.

1. Introduction

Induction cookers have become necessary kitchen tools and are widely used across the world. The increasing demand for induction cookers has resulted in many recognized manufacturers producing more reliable and affordable cookers. To improve the performances of induction cookers, a great deal of research has been carried out in the past few decades [1,2]. Most of these efforts were focused on how to increase energy efficiency, reduce manufacturing and use costs, and meliorate the safety performances of the cookers. Much attention has been paid to the heat transfer problems of induction cookers [3]. As the standards of living are improving, however, people are becoming more concerned with the comfort of their kitchens. Accordingly, the acoustical properties of induction cookers, which influence people's health, have become very important. It is known that the noise of an induction cooker is not easy to predict and reduce due to the complex coupling characteristics of the thermodynamics, hydromechanics, and aeroacoustics of the flowing gas within it.

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Fortunately, with the great advancements in both computer capability and numerical algorithms in the past twenty years, computational aeroacoustics has undergone rapid development [4,5]. The coupling processes of the air flows in induction cookers result in three typical difficulties in computational aeroacoustics: (1) the extremely wide range of flow scales, which makes any single computational method insufficient; (2) the extremely small fraction of sound energy compared with that of flow energy, which means that a small error in the flow simulation would lead to a large error in the sound prediction; (3) and the treatment of the numerical boundary conditions. To overcome these problems, Bell described a parallel finite volume method (FVM) [6], which Dou and Phan-Thien have successfully applied to solve three-dimensional viscoelastic flows [7]. In the FVM algorithm, the system matrix is not stored and the sequentially iterative solutions strategy for the governing equations is employed. The parallel implementation of the FVM shows great memory-saving advancements so it can be used to solve much larger problem. Using the large eddy simulation (LES), the energy effect of the small eddies were simulated and analyzed by De Stefano [8], Usera [9], and Lee [10]. In these works, the LES was performed for a flow turbulence analysis. Because refined mesh is needed for simulation using LES, so, considerable computer power is needed. Acoustic analogies pioneered by Lighthill are based on an exact linear wave equation for density [11]. All nonlinear effects are accounted by the Lighthill stress tensor, which acts as the sound source. Curle extended the Lighthill analogy to include the effects of solid boundaries [12]. Ffowcs Williams and Hawkings generalized the Curle solution to incorporate the arbitrary motions of aerodynamic surfaces and derived the FW-H equation, which is the most general form of the acoustic analogy [13]. Since the early 1970s, the FW-H equation has been used with much success in the prediction of the degrees of noise emitted by helicopter rotors, propellers, and fans [14]. Farassat has a number of expository publications that were aimed at building the mathematical background necessary to work with the FW-H equation [15–17]. Farassat proved that the FW-H acoustic analogy can handle surfaces in motion, and that the surface can be permeable, allowing mass, momentum, and energy to pass through it [18,19]. Obviously, for a system with solid boundaries, such as an induction cooker, the FW-H analogy algorithm (FWH-AA) is the most applicable for aeroacoustic computations.

This paper presents a three-dimensional hybrid technique for calculating the acoustical properties of induction cookers through computational aeroacoustics. This technique, the FVM–LES-AAM, is a combination of the FVM, the LES, and the FWH-AA. Experimental verifications suggest that the FVM–LES-AAM is accurate and feasible for acoustical predictions of induction cookers. Following the modeling and simulation procedure, the sample induction cooker was redesigned for noise reduction by partly changing its component structures and/or positions. Considering the temperature characteristics simulated by the CFD method, some constructive conclusions were drawn, which were very instructive and useful for induction cooker designs.

2. FVM–LES-acoustic analogy method

2.1. LES equations and numerical method

In the LES the flow variables are decomposed into large- and subgrid-scale components. The large-scale component is defined by the filtering operation [20],

$$\bar{\phi} = \int_D \phi G(x, x')dx', \tag{1}$$

where ϕ is a generalized variable; $\bar{\phi}$ is a filtered generalized variable; D is the entire computational domain; G is the grid filter function; and x' and x are the spatial coordinate and the filtered spatial coordinate, respectively. $G(x, x')$ can be denoted by many methods, and in this study, the FVM was used to average the variable in the control volume V so $G(x, x')$ is defined as:

$$G(x, x') = \begin{cases} 1/V & x' \in V \\ 0 & x' \notin V \end{cases} \tag{2}$$

Substituting Eq. (2) into Eq. (1), the filtering function was obtained base on the FVM,

$$\bar{\phi} = \frac{1}{V}\int_D \phi dx'. \tag{3}$$

The filtered governing equations [20] were obtained by applying the filter function above as follows:

$$\frac{\partial}{\partial t}(\rho\bar{\phi}) + \frac{\partial}{\partial x_i}(\rho\bar{\phi}\bar{u}_j) = -\frac{\partial\bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial\bar{\phi}}{\partial x_j}\right) - \frac{\partial\tau_{ij}}{\partial x_j}, \tag{4}$$

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho\bar{\phi}\bar{u}_j) = 0, \tag{5}$$

where x_i and x_j $(i, j = 1, 2, 3)$ are the coordinates X, Y, and Z; u_j is the filtered velocity components $\bar{u}$, $\bar{v}$, and $\bar{w}$ along with X, Y, and Z, respectively; $\bar{p}$ is the filtered pressure; μ is the molecular viscosity coefficient; ρ is the fluid density; τ_{ij} is the subgrid