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Time-Periodic Mechanisms of Shock Interactions for High Enthalpy Reacting Flow over Double Wedges at Mach 7

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Abstract –The present study investigates the time-periodic characteristics of a 2-dimensional high enthalpy (8MJ/kg) flow at Mach 7 over double wedges with fixed fore angle of $30^{\circ}$and aft angles of 45°, 50°, 55°, and 60°. Although one can find considerable amounts of numerical and experimental studies in the literature, they mainly focus on non-reacting flows over a double wedge. The present study examines the effects of chemical reactions on time-periodic mechanisms of high enthalpy reacting flow in equilibrium. The effects of aft angle on physics of the flow are investigated by comparing the chemical compositions and wall heat flux distributions for each aft angle considered. For this purpose, an open-source *hyperReactingFoam* solver which is capable of modelling hypersonic reacting flows in equilibrium and non-equilibrium conditions is used.

***Keywords*:** Shock-shock interactions, shock-boundary layer interactions, high enthalpy reacting flow, equilibrium flow, time-periodicity

1. Introduction

Shock-shock interactions can be observed around supersonic aircrafts, re-entry vehicles and through supersonic inlets. Understanding the physics of such interactions is crucial since they can lead to considerable thermal and pressure loads on the vehicle, which may result in structural damage. Swantek and Austin [3] studied the problem both for low (2.1 MJ/kg) and high (8 MJ/kg) enthalpy flows over a double wedge with fore angle of 30° and aft angle of 55° experimentally. They investigated the physics of the flow for Mach numbers ranging from 4 to 7. Patil et al. [4] examined both low and high enthalpy flows of nitrogen, N_2 at Mach 7 over a 30°-55° double wedge numerically and observed that the high enthalpy flow was unsteady. Reinert et al. [5] studied nonequilibrium Mach 7 flow over a 30°-55° double wedge in 3-dimensions. They performed analyses both for low and high enthalpy flows and observed low-frequency oscillations in the flow field for both cases. Durna and Celik [6] focused on long term behaviour of shock interactions for low enthalpy Mach 7 flow over a double wedge with fore angle of 30° and aft angles ranging from 45° to 60°. They reported that the flow was time-periodic when the aft angle was greater than 47° and the time required to observe periodicity was increased with an increase in the aft angle. Tumuklu et al. [7] investigated high enthalpy non-reacting flow of Mach 7.1 over a 30°-55° double wedge both in 2- and 3-dimensions. They recorded the pressure data at two locations which were in the vicinity of the triple point and inside the separation zone by using Fast Fourier Transform (FFT) method. According to their FFT analyses they reported that both for the two locations the most dominant frequencies were 2.6 and 2.4 kHz for 2- and 3-dimensional cases, respectively.

There are considerable amount of studies in the literature focusing on shock interaction mechanisms over double wedge and double cone geometries. These studies have examined the physics of the flow in thermal and chemical equilibrium. Their findings have shown that the physics of shock interactions are time periodic. To the best knowledge of the researchers, the effects of chemical reactions on time periodicity have not been studied numerically before. The present study focuses on a high enthalpy (8 MJ/kg) M=7 reacting flow over a double wedge. The problem will be examined for a total of four different

wedge configurations with fixed fore angle of 30° and aft angles of 45°, 50°, 55°, and 60°, respectively. The effects of aft angle and the chemical reactions on the time-periodic behavior of shock interactions will be investigated. For this purpose, temporal characteristics of the reacting flow of air will be studied by using a pre-validated [1,2] open-source nonequilibrium solver called *hyperReactingFoam*, which was developed by Vatansever and Celik. The solver was developed by using a combination of the two standard solvers in OpenFOAM software. The former and later solvers are the rhoCentralFoam solver, which has the capability of capturing shock structures in supersonic flow and the reactingFoam solver, which is able to analyse chemical reactions in incompressible flow. Therefore, *hyperReactingFoam* can model shock-shock interactions and the chemical reactions occur in hypersonic reacting flow both in equilibrium and non-equilibrium. The pressure and temperature fields, the mass fractions of oxygen, O_2 and N_2 will be recorded in the vicinity of the triple point and at a point inside the separation zone. In addition, to investigate the effects of chemical reactions on time-periodicity of the flow, the temporal variation of the heat transfer in normal direction to the wall will be tracked at 6 stations along both surfaces of the wedge based on the study of Durna and Celik [6]. To understand the physics of the flow further, FFT analyses will be performed on the flow field data. Obtained results will be compared for each configuration to examine the effects of aft angle on time-periodicity of the flow.

2. Computational Details and Modelling of the Problem

2.1. Governing Equations

The governing equations of unsteady, compressible and viscous flow of reacting gases in thermal equilibrium are the continuity, momentum, energy and species' transport equations which can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \mathbf{UU}) + \nabla \mathrm{p} - \nabla \boldsymbol{\tau} = 0, \tag{2}$$

$$\frac{\partial \rho \mathrm{E}}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathrm{E}) + \nabla \cdot (\mathbf{U}\mathrm{p}) - \nabla \cdot (\boldsymbol{\tau}\mathbf{U}) + \nabla \cdot \left(- \mathrm{k} \nabla \mathrm{T} - \sum_{s} h_s \mathbf{J_s} \right) = 0, \tag{3}$$

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{U}) - \nabla \cdot (\mathbf{J_s}) = \dot{w}_s, \tag{4}$$

where, $\boldsymbol{U}$,E and $\boldsymbol{\tau}$ represents velocity vector, total energy and stress tensor, respectively. k corresponds to thermal conductivity and $\dot{w}$ is the mass production terms. Subscript "s" corresponds to the s-th species in the gas mixture. $\dot{w}_s$ is the reaction source term which represents formation or destruction of chemical specie's in the mixture. $\mathbf{J_s}$ and h_s are the mass diffusion and enthalpy of specie's, respectively.

They are evaluated as follows:

$$\dot{w}_s = \mathrm{M_s} \sum_{r=1}^{N_r} (v''_{s,r} - v'_{s,r}) \left[k_{f,r} \prod_{k=1}^{N_r} \left(\frac{\rho_k}{M_k} \right)^{v'_{k,r}} - k_{b,r} \prod_{k=1}^{N_r} \left(\frac{\rho_k}{M_k} \right)^{v''_{k,r}} \right], \tag{5}$$

$$\mathbf{J_s} = \rho D_s \nabla Y_s, \tag{6}$$

where, M_s and D_s are the molecular weight and the diffusion coefficient for specie's. $\mathrm{N_r}$ corresponds to the number of reactions occur in the mixture. $v''_{s,r}$ and $v'_{s,r}$ represents forward and backward stochiometric coefficients, while $k_{f,r}$ and $k_{b,r}$ denote forward and backward reaction rates, respectively.

A reacting air model [8] which consists of 5 species ($\mathrm{N_2}$, $\mathrm{O_2}$, N, O, and NO) and 19 chemical reactions is taken into account. To calculate the thermodynamic properties such as heat capacity, entropy and enthalpy, an extended JANAF package [1,2]

which is modified by Vatansever and Celik for a greater temperature range of 200-20000 K is used. A detailed explanation of the numerical method and other features of the solver can be found in the reference studies [1,2].

2.2. Computational Mesh and Boundary Conditions

Figure 1 shows the boundary surfaces of the 2-dimensional domain that is generated based on the experimental study of Swantek and Austin [3]. The computational mesh is created by using the blockMesh utility of OpenFOAM with total number of cells of 296400 as a result of the grid convergence study of Durna and Celik [6]. Mesh resolutions near to the compression and expansion corners are increased and non-dimensional wall normal distance value, y^+ of less than 1 is maintained in the mesh. Freestream conditions tabulated in Table 1 are imposed at the boundary of inlet that is shown in Figure 1. The initial conditions of each species are listed in Table 2.

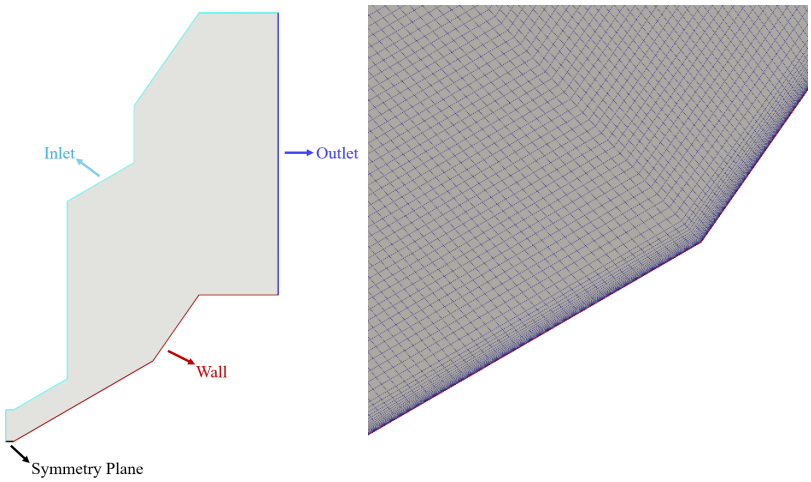

Fig. 1: Boundaries of the computational domain (left) and a close-up view of the compression corner mesh (right) [6].

2.3. Validation

To validate the solver, heat flux distributions along the surfaces of the wedge are compared with the experimental study of Swantek and Austin [3] and numerical results of Vatansever and Celik [2]. For this purpose, time averaged heat flux normal to the wall is obtained in time interval of $80 - 242$ μs. Obtained results are shown in Figure 2. One can observe that the present study is also able to accurately estimate the location of the peak heat flux along the surfaces of the wedge.

Table 1: Freestream conditions for high enthalpy flow adapted from Swantek and Austin [3].

Mach number	Unit Reynolds, 10^6 / m	Static temperature	Stagnation enthalpy	Static pressure	Velocity	Density	Test time
-	m^{-1}	K	MJ/kg	kPa	m/s	kg/m^3	μs
7.14	0.44	710	8.0	0.78	3812	0.004	242

Table 2: Initial mass fractions of the mixture for equilibrium flow [1,2].

Y_{N_2}	Y_{O_2}	Y_{NO}	Y_N	Y_O
0.767	0.233	0.0	0.0	0.0

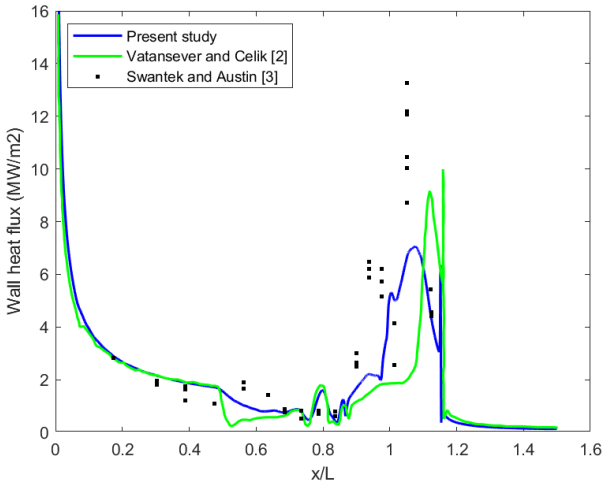

Fig. 2: Comparison of wall heat flux distributions along the surfaces of the wedge the references.

3. Conclusion

Physics of shock interactions over a double wedge will be investigated to demonstrate the temporal characteristics of a high enthalpy reacting flow in equilibrium. The effects of chemical reactions in the mixture on time-periodicity of the flow will be examined. In order to investigate the unsteady nature of the interactions, analyses will be performed considering four different geometric configurations where fore angle is set to be 30° and varying aft angles are 45°, 50°, 55°, and 60°, respectively.

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