Numerical study on passive convective mass transfer enhancement

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Abstract. Passive mixing mechanisms are widely used for heat and mass transfer enhancement. Vortices generated in flowfield lead to gradients that favour convective mass transfer. Computations on enhancement of convective mass transfer of sublimating solid fuel by baroclinic torque generated vortices in the wake of a swept ramp placed in high speed flow is presented here. Advection Upstream Splitting Method (AUSM) based computational scheme employed in the present study, to solve compressible turbulent flow field involving species transport, could capture the complex flow features resulted by vortex boundary layer and shock boundary layer interactions. Convective mass transfer is found to get improved in regions near boundary layer by horseshoe vortex and further transported to other regions by counter rotating vortex pair. Vortices resulted by flow expansion near aft wall of wedge and recompression wave-boundary layer interactions also promotes convective mass transport. Extensive computations have been carried out to reveal the role of vortices dominance at various lateral sweep angles in promotion of convective mass transfer in turbulent boundary layer.

1. Introduction
Passive mixing devices are widely used in conjugate heat and mass transfer applications such as chemical processing systems, hybrid rocket propulsions systems, refrigeration systems, and thermal protection systems. Promotion of mixing leads to improvement of performance and operational efficiencies of such systems; thereby energy and environmental issues associated with such systems can be brought down considerably. Passive mixing devices are often simple to implement in practical applications that do not require any power or external interference. Vortices generated by solid boundary features such as winglets sharp edges surface protuberance features [1, 2] have been widely investigated by many researchers over the last few decades for the possible improvement in heat/mass transfer effects.

Compressible turbulent flows in passive mixing devices involves complex flow features such as shock/expansion waves and their interaction with boundary layers associated with solid surfaces. It generates sharp gradients in flowfield. Misaligned gradients of the flow variables such as pressure and density and presence of viscous stress in density gradient generate baroclinic torque induced vortices [3]. Vorticity generated by this effect will be perpendicular to density is given by

$$\frac{D\omega}{Dt} = \frac{\omega}{\rho} \nabla u + \frac{1}{\rho^3} \nabla \rho \times \nabla p$$

Baroclinic torque induced vortex generated in a high speed flow past a swept ramp and its role promotion of convective mass transfer is analysed in the present study. A schematic of major features in this flowfield is given in figure 1. Flow expands as it spills over the ramp and thereby produces low pressure region near to the wall. This results in the baroclinic torque induced vortex generation. Large scale streamwise vortex develops when flow spills over the ramp which advects more fluid in the free stream.
to the centre. Horseshoe vortices generated by flow separation behind the ramp moves downstream in boundary layer region. Counter-rotating vortex pairs have been observed in both vortex systems. These vortex systems die out due to the viscous effects in developing turbulent boundary layer. Species evolved by the vaporisation of solid fuel gets transported to the mixing zone initially by the horseshoe vortices and later carried by streamwise counter-rotating vortex pair. In this process fuel gets mixed up well with high speed oxidiser stream as the vortex system provides low velocity region to promote molecular diffusion.

Vortex system in the flow field depends on sweep angle of the wedge. Role of sweep angle in enhancing mass transfer from a mass evolving boundary is analysed in the present computational study.

2. **Background**

Literature review focus on previous work reported in the field of convective heat/mass transfer enhancement using passive methods based on typical surface features. A summary of major contributions has been presented in table 1.

| Authors          | Experimental Methodology                                                                 | Results                                                                 |
|------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Gentry et al     | Used delta wing Vortex generators (VG) on flat plate for Heat transfer enhancement and also to modify a developing channel flow | Noticed a 50 – 60% enhancement in flat plate and a 300% increase of local heat transfer coefficient in developing channel flow |
| Bruce et al      | Experimental investigation of the development and structure of stream wise vortices embedded in a turbulent boundary layer | Observed an enhanced circulation decay in arrays of closely packed vortices that may be due to the merging of neighbouring counter rotating vortex cores |
| Promvonge et al  | Investigated the effects of combined ribs and winglet type VGs                           | Inline ribs shows highest increase in Nusselt number and staggered ribs shows better thermal performance. |
| Debora et al     | Studied the vortex produced by a simple round wall jet with a 2D turbulent boundary layer | Max vorticity levels strongly dependent on skew angle and jet velocity and obtained skew angle is between 45 – 90 deg |
Liou et al [9] Investigated heat transfer and fluid flow in a square duct with 12 different shaped vortex generators

Direction and strength of secondary flow with respect to heat transfer wall is the most important factor which promotes heat transfer enhancement.

Petersen et al [10] Investigated baroclinic vortex production

They found that local azimuthal temperature gradients introduces vorticity.

Storey et al [11] Effect of vortices on the frost growth in developing channel flow

Noted a 7% increase in the frost growth with the induced stream wise vortices.

Henze et al [12] Investigated longitudinal tetrahedral VGs

Found that ratio between height of VG and hydrodynamic boundary layer thickness will affect the heat transfer enhancement.

Azize [13] Delta wing type VGs

Experimentally studied the flow structure in horizontal ducts having double rows of half delta wing VGs.

3. Governing Equations

Present problem involving mass transport enhancement in Baroclinic induced vortex mass transfer enhancement can be modelled using conservative form of Navier-Stokes equations which govern a three dimensional turbulent compressible flow incorporating fuel and oxidizer species as follows.

\[
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} + \frac{\partial H}{\partial z} = S
\]  

(2)

Where \( U \) is the vector of all conservation variables. \( F \) and \( G \) are fluxes in \( x \) and \( y \) directions, and \( S \) is the vector of source terms.

The turbulence model used in the present study is SST \( \kappa-\omega \) two equation model [14].

4. Numerical Modelling

In the present study, AUSM [15] scheme available in a Finite Volume Method (FVM) based commercial package (Ansys Fluent), has been made use for the inviscid flux computations. Key aspect of the present problem is implemented in conjunction with boundary conditions given on fuel layer represented in bottom of the computational domain. The schematic of mass and energy exchange process occurring in the convective mass transfer boundary layer is shown in in figure 2.

Figure 2. Modelling of Mass and Energy balance

Simulations have been performed on 3D computational domain to compare the enhancement due to baroclinically induced vortex interaction. The Computational domain consists of a flat hydrocarbon fuel layer undergoing mass transport in simple convective boundary layer as shown in figure 3. A simple flow manipulator (swept ramp) is placed on the flat hydrocarbon fuel layer to create vortices so as to bring in effect of the vortex boundary layer interaction in flat fuel layer. Geometry and dimensions of the ramp are as given in figure 3. The computational domain were initially discretized with \( 8 \times 10^5 \) control
volumes and later refined to $1.6 \times 10^6$ level for which convergence of species profile has been attained. The entire computational domain was initialized with oxidizer fluid inflow conditions. Grid is refined near all no-slip walls and near to the swept ramp, by giving biasing in direction normal to no-slip walls, maintaining a $y+$ of 1. For the present density based solver using explicit time integration, convergence of the order of $10^{-5}$ for all residuals has attained after 125000 iterations with a CFL of 0.5.

5. Results and Discussion

The computational procedure was validated using experimentally measured centreline wall pressures for a similar ramp placed in supersonic flow [16]. Streamline plot of the computed results for the 3D domain is given in figure 4. All salient flow features, described before (figure 1), has been captured. Velocity magnitudes associated with regions of vortex boundary layer interaction as well as counter rotating vortex pair are observed to be relatively smaller compared to other regions. This enables the formation of gradients favouring enhancement of mass transfer.

5.1. Flow features

A plot of computed streamlines in the flow field is given in figure 4. A boundary layer develops on fuel surface when approaching oxidizer flow interacts with it, due to no-slip boundary condition given on the surface. A strong oblique shock is developed at the leading edge of swept ramp. Boundary layer separates in the region of interaction of expansion wave with boundary layer. Reattachment compression wave is also generated from the boundary layer after the ramp. A high temperature gradient region also formed upstream of expansion wave reattachment. A low velocity recirculation region is formed in the wake region of ramp. In short, the present flow field of shock interaction with developing boundary layer on a convective mass transfer boundary layer involves many zones of sharp gradients.
5.2. Effect of Swept ramp on mass transfer

Three swept ramp configurations are used in the present study viz. No sweep, 5° sweep and a 7° sweep. Field plot showing the lift of species from the plate is shown in figure 5. Two longitudinal counter rotating vortex pair are generated along the slanting surface of the ramp along with lateral vortices due to the sweep given in the ramp. Enhancement in mass transfer coefficient is observed in two regions along the axial direction as shown in figure 6. First enhancement is observed at the wake region of the ramp and the latter at a region where the baroclinic torque induced vortices are predominant. This enhancement in mass transfer improve further with increase in sweep angle of wedge. This is due to the dominance of vortex with given amount of sweep. Spanwise variation of mass transfer coefficient at wake region of the swept ramp and baroclinic torque induced regions are plotted in figure 7 and 8. Aforementioned enhancement are observed in spanwise direction as well.

![Field plot showing the lift of species from the plate for 7° Sweep (a) and 5° Sweep (b)](image)

**Figure 5.** Field plot showing the lift of species from the plate for 7° Sweep (a) and 5° Sweep (b)

![Enhancement in mass transfer along the axial direction for different Swept angles](image)

**Figure 6.** Enhancement in mass transfer along the axial direction for different Swept angles

![Enhancement in mass transfer for spanwise direction in the wake region](image)

**Figure 7.** Enhancement in mass transfer for spanwise direction in the wake region
Figure 8. Enhancement of mass transfer for spanwise direction (baroclinic torque induced region)

6. Conclusions

Three dimensional compressible turbulent flow field with mass transport of sublimating fuel has been simulated using AUSM scheme available in a FVM based solver. Computational procedure has been validated using experimental results and scheme was found to be robust in negotiating sharp gradients resulting due to shock/vortex interactions with boundary layer. Extensive computations have been performed to reveal the role of lateral sweep of vortex generator for convective mass transfer enhancement in high speed flows. Misalignment of isopycnals and isobars becomes more dominant in flow field with higher sweep angles, which leads to production of baroclinic torque induced vortices. Enhancement of mass transfer is observed to be prominent in two regions of the flow field viz. in the wake region of the swept ramp and baroclinic torque induced vortex region. Enhancement of convective mass transfer in spanwise direction, resulted by mass transport in counter rotating vortex pair, is also improved with sweep angle. This establishes the sweep angle factor of wedge-based vortex generators in passive mixing systems.

References

[1] Webb, R. L. and Kim, N. H., 1994. *Taylor Francis: New York, NY, USA*.
[2] Jacobi, A. M. and Shah, R. K., 1995. *Experimental Thermal and Fluid Science*, 11, p 295-309.
[3] Waitz, I., Marble, F., and Zukoski, E., 1991. AIAA Journal, 31, p 3140.
[4] Gentry, M. C. and Jacobi, A. M., 1997. *Experimental Thermal and Fluid Science*, 14, p 231-42.
[5] Gentry, M. C. and Jacobi, A. M., 2002. *Journal of heat transfer*, 124, p 1158-168.
[6] Wendt, B. J., Greber, I., and Hingst, W. R., 1993. AIAA journal, 31, p 319-25.
[7] Promvonge, P., Chompookham, T., Kwankaomeng, S., and Thianpong, C., 2010. *Energy Conversion and Management*, 51, p 1242-249.
[8] Compton, D. A. and Johnston, J. P., 1992. AIAA journal, 30, p 640-47.
[9] Liou, T. M., Chen, C. C., and Tsai, T. W., 2000. *Journal of Heat Transfer*, 122, p 327-35.
[10] Petersen, M. R., Julien, K., and Stewart, G. R., 2007. The Astrophysical Journal, 658, p 1236.
[11] Storey, B. D. and Jacobi, A. M., 1999. *International Journal of Heat and Mass Transfer*, 42, p 3787-802.
[12] Henze, M. and Von Wolfersdorf, J., 2011. *International Journal of Heat and Mass Transfer*, 54, p 279-87.
[13] Akyayoglu, A., 2011. *Experimental Thermal and Fluid Science*, 35, p 112-20.
[14] Menter, F. R. 1994, AIAA journal, 32, p 1598-605.
[15] Liou, M. S. and Steffen, C. J., 1993. *Journal of Computational physics*, 107, p 23-39.
[16] Donohue, J. M. and cDaniel, J. C., 1996. *AIAA journal*, 34, p 455-62.