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LES SIMULATION OF SCREECH COMBUSTION INSTABILITY IN A MODEL AERO-GAS TURBINE AFTERBURNER

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Abstract

Large eddy simulation of reacting flow past a high blockage V-gutter has been performed. The goal of the present study was to provide a quantitative description of screech and to address the very basic question that, can the present CFD model reproduce the results as observed in an experimental study? A systematic approach has been used to answer this question. Initially, a validation study had been carried out using published literature. For the validation study, a non-reacting flow past a low blockage V-gutter had been considered. For both 2-D and 3-D geometries, the centerline mean axial velocity profiles and Strouhal numbers had been compared with experimental and earlier LES work. Once the LES results had been verified with the published work, the reacting flow past a high blockage V-gutter was simulated using LES. The present study was successful in modeling the transverse combustion instabilities. Frequencies of oscillation were well matched with the experimental values. In addition, flow features such as asymmetric vortex shedding during the transverse screech combustion instability matched with the experimental high speed shadowgraphs.

Introduction

The prediction of combustion instabilities has been one of the most difficult challenges faced in the predesign stage of an afterburner combustion system. Combustion instabilities are thermo-acoustic phenomena, that occur when spatial-temporal coupling of pressure and heat release fluctuations are in phase. The pressure oscillations associated with these instabilities pose a serious danger to the combustion system. Screech is characterized by large pressure oscillations with high frequencies (800Hz -5000 Hz) along with the high-pitched sound, associated with the transverse acoustic mode of the duct. Attempts to predict these instabilities have led to the development of a large number of analytical and numerical tools.

In a typical gas turbine afterburner, liquid fuel that is injected by the spray bar gets atomized and evaporates due to the hot environment and then the fuel-air mixture gets burnt in the recirculation zone provided by the V-gutter. The ability of a flame holder to sustain the flame without blowout is called static stability, Briones et. al. [1]. On the other hand, oscillation of a flame may occur if the unsteady heat release rate and one of the acoustic modes of duct are in phase. The flow structure behind the V-gutter consists of separated layers and a wake. These shear layers may be subjected to a Kelvin-Helmholtz(KH) type instability which is a symmetric pairing of vortices in the shear layer or it could be subjected to a Benard/ von Karman(BvK) type instability which is an asymmetric shedding of vortices from the edge of the flame holder. This shedding could cause flame oscillations, which may lead to flame blow out or dynamic instabilities. The objective of this investigation were to (1) Validation of current LES results with published results for a non-reacting case (2) Model the transverse combustion instabilities (SCREECH) for the reacting case and validate the results with experiments

Numerical Model

The present work employed the Large Eddy Simulation (LES) technique, which was a solution of the full, nonlinear conservation equations in Computational Fluid Dynamics (CFD), to predict the transverse combustion instability (also known as SCREECH) in a 2-D rectangular model aero-gas turbine afterburner. The Commercial Code ANSYS FLUENT 14.0 had been used to carry out this study. The governing conservation equations of

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continuity, momentum, energy, species had been solved using a COUPLED solver of FLUENT. For SGS (sub-grid scale) modelling the Dynamic Smagorinsky's model had been used as recommended by Menter [2]. For reacting flow, combustion was assumed premixed, single step with a finite-rate/eddy-dissipation model.

Computational Domain, Mesh, Boundary Condition and Initial condition

Validation Case: Figs. 1, 2 and 3 show the computational domain and mesh used for the validation study with the related dimensions. For the validation study (2-D and 3-D geometry with depth 70 mm), the flow was considered non-reacting with the inlet defined as a velocity inlet. Inlet velocity was taken as 16.2 m/s and the inlet temperature as 300 K. The outlet condition was defined as a pressure outlet with atmospheric pressure (92 kPa). Solution was initialized with a k-ε RANS solution and then switched to LES with a time step of 1e-5 s, and 40 inner iterations per time step.

Screech Case: For the LES of reacting flow with a high blockage V-gutter, Fig. 4 shows the geometry and mesh used in the simulation. Geometric details and boundary conditions were chosen from the experimental study by Rajashekar et. al [3]. The inlet condition was defined as a pressure inlet with total pressure of 1.4E+5 Pa and temperature of 600 K and the outlet as pressure outlet with atmospheric pressure (92 kPa). Kerosene was used as the fuel with the following composition (mass fraction) at the inlet, (corresponding to afterburner inlet); $C_{12}H_{23}$=0.0374, O_2=0.1714, CO_2=0.0460, H_2O=0.01804 (overall equivalence ratio = 0.8). Solution was initialized with a k-ε RANS solution and then switched to LES with a time step of 1e-5 s, and 40 inner iterations per time step.

Results and Discussion

Validation Case: Fig. 5 shows the comparison of time averaged centerline axial velocity, where X-axis (Nx) is the axial distance normalized by the V-gutter height and Y-axis (Ux) was averaged axial velocity normalized by the inlet velocity. Fig. 5 clearly shows that the current 2-D LES matched very well with 2-D LES performed by the Briones et. al. [1]. It was also clear that 2-D simulation (Briones et. al. [1] and current study) have issues predicting the recirculation zone as measured by Kiel et. al. [4]. Briones et. al.[1] defined the recirculation zone length, as difference between the two location of the zero axial velocities adjacent to the global minimum axial velocity. For two dimensional case, recirculation zone length is longer than the recirculation zone length measured by the Kiel et. al[4], and shifted towards the inside of the V-gutter. Similar results were reported by Briones et. al. [1]. On the other hand, the dynamic behaviour had been predicted correctly as shown in Fig. 6. Earlier work by Shambhoo et. al. [5] had also shown the presence of Benard-Von Karman vortex shedding; similar results (Fig. 6) were observed in the current LES work. Fig. 7 shows the velocity flucultation behind the V-gutter and its corresponding FFT. The dominant frequency of oscillation was 97.13 Hz, which coresponds to a Strouhal number of 0.23 for the 2-D case. For the 3-D geometry (Fig. 3) time averaged centreline axial velocity (Fig. 8) matched very well with the experimental result of Kiel et. al. [4], along with a correct prediction of mean recirculation zone length. FFT of the time series of the velocity (Fig. 9) showed that the frequency of vortex shedding was 109.9 Hz, which corresponded to a Strouhal number of 0.264. Kiel et. al. [4] had also reported a similar Strouhal number (0.25) for the non-reacting case. Hence, the present LES study was successful in predicting flow features reported by earlier work. Since the 2-D simulation had predicted the dynamic behaviour of vortex shedding correctly, further simulation of the reacting flow with high blockage V-gutter was continued with the 2-D geometry only.

Screech Case : Earlier work (Shambhoo et. al. [5]) on non-reacting flow past a high blockage V-gutter had shown that periodicity of Y-velocity oscillation was lost at high blockage, but velocity fluctuations were of the order of the axial velocity and this could serve as driver for screech. The inlet parameters, namely inlet pressure=1.4E+5 Pa, inlet temperature = 600 K, overall equivalence ratio = 0.8 from an experimental study, Rajashekar et. al [3], corresponding to screech conditions were used to simulate the transverse combustion instability. Fig. 10 gives the sequence of images showing transverse oscillation, which indicate how the high pressure region moves from the top to the bottom and back within 49 μs (which corresponds to 2040 Hz). Fig. 11 shows the evolution of pressure oscillation from stable to unstable combustion. FFT shows that the dominant frequency of these oscillation were 2063 Hz, which was in the range of frequency (1900 Hz – 2100 Hz) observed during the experiments, Rajashekar et. al [3]. Fig. 12 shows the typical FFT of pressure oscillation during the experiment. The transverse mode frequency observed was 1951 Hz for the same operating condition. The numerical shadowgraph (Fig. 13) also showed the presence of asymmetric vortex shedding, which is similar to the experimental observation by Rajashekar et. al [3] as shown in Fig. 14. In order to confirm that these oscillations were transverse, a relative comparison of the pressures measured at point 1 (top wall) and point 2 (bottom wall) (Fig. 4)was carried out. Fig. 15 clearly shows that these two signals were out of phase with each other, which proves that the mode of the combustion instability was transverse (As shown earlier in Fig. 10).

Conclusions:

LES simulation of the non-reacting flow past a low blockage V- gutter was validated with published literature. 2-D simulation was successful in predicting the dynamic behavour of vortex shedding in the wake of a V-gutter. 3-D results matched perfectly with experimental results and earlier LES work. Reacting flow past a high blockage V-gutter was simulated, and the high frequency transverse combustion instability(screech) was successfully captured in the simulation. The frequency of pressure oscillation was in agreement with the experimental observation. Flow structure behind the V-gutter was very close to what was observed during the experiments with the high speed shadowgraphs; in both cases, asymmetric vortex shedding was observed. In addition to that, out of phase signals at the top and bottom wall were one of the features, that matched with the earlier experimental work. Present CFD simulation was sucessfully in simulating the screech condition in a model afterburner and provides a strong foundation for developing a novel computational method to predicted screech in a given afterburner geometry.

References:

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(5) Shambhoo, G Sriram, S Chenthil Kumar, K Vijaya Sankaran, H S Raghukumar, M Janaki Rami Reddy, C Rajashekar, K Ashirvadam, and J J Isaac, "*On the Flow Past a High-Blockage V-Gutter Flameholder: Implications on the Onset of Screech*", 19th Annual Ae.S.I. CFD Symposium, August 10th -11th, 2017, Bangalore

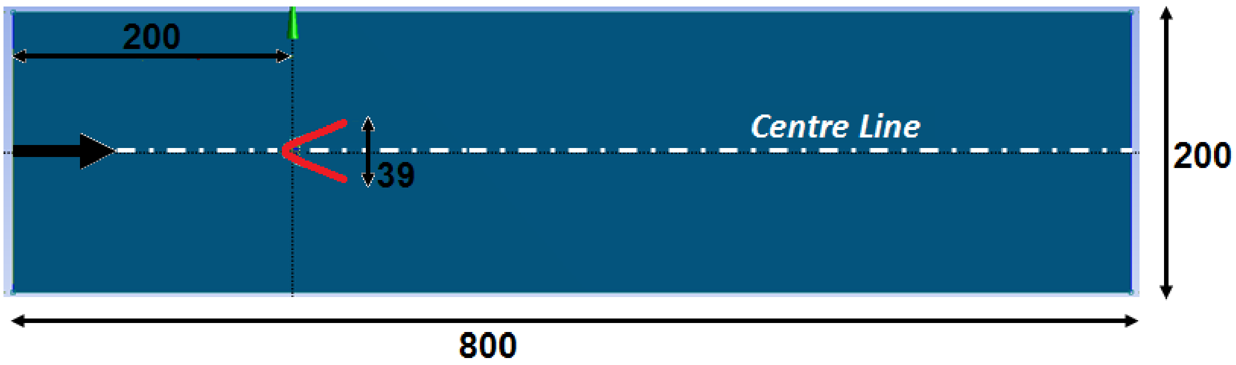

Fig. 1: Computational domain for the 2-D case with a low blockage V-gutter for the validation study

(All Dimensions are in mm)

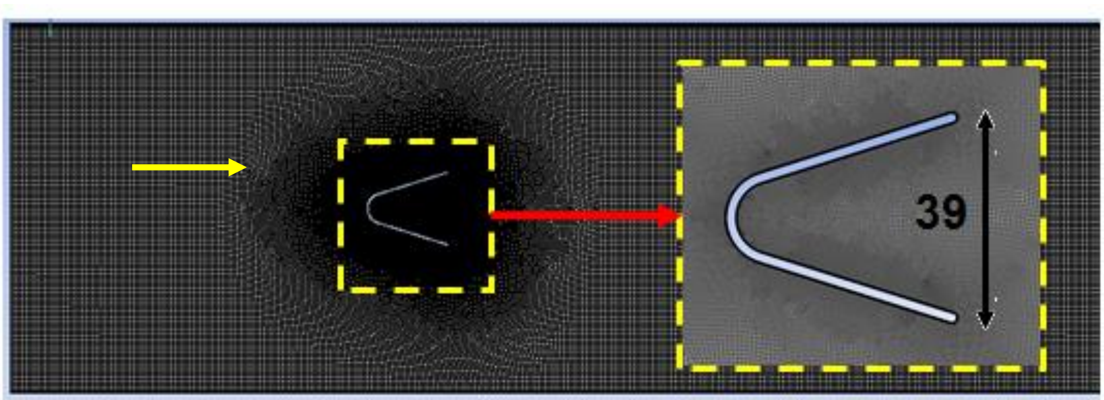

Fig.2: Mesh of the computational domain for 2-D case showing dense mesh near the V-gutter region

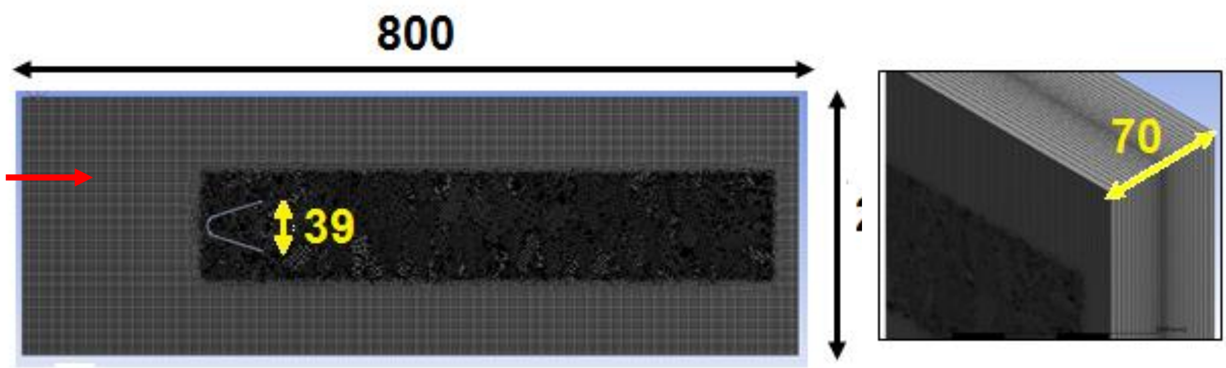

Fig. 3: Computational domain for the validation study of the 3-D geometry with a low blockage V-gutter
(All Dimension are in mm)

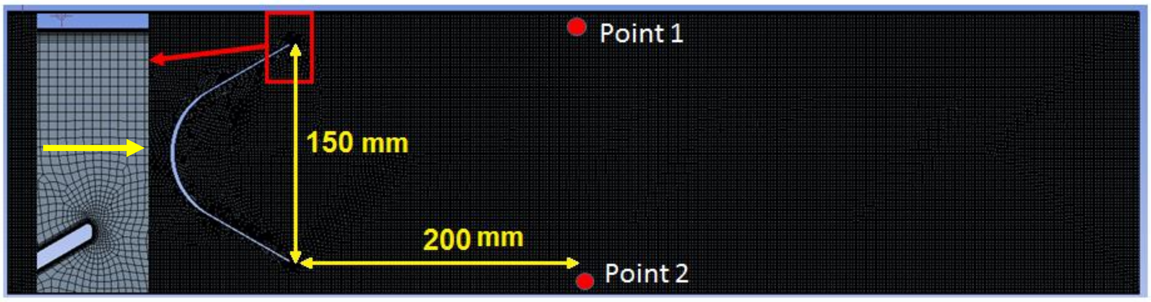

Fig. 4: Geometry and Mesh for reacting flow past a high blockage V-gutter (Point 1 and Point 2 are 12 mm away from the wall)

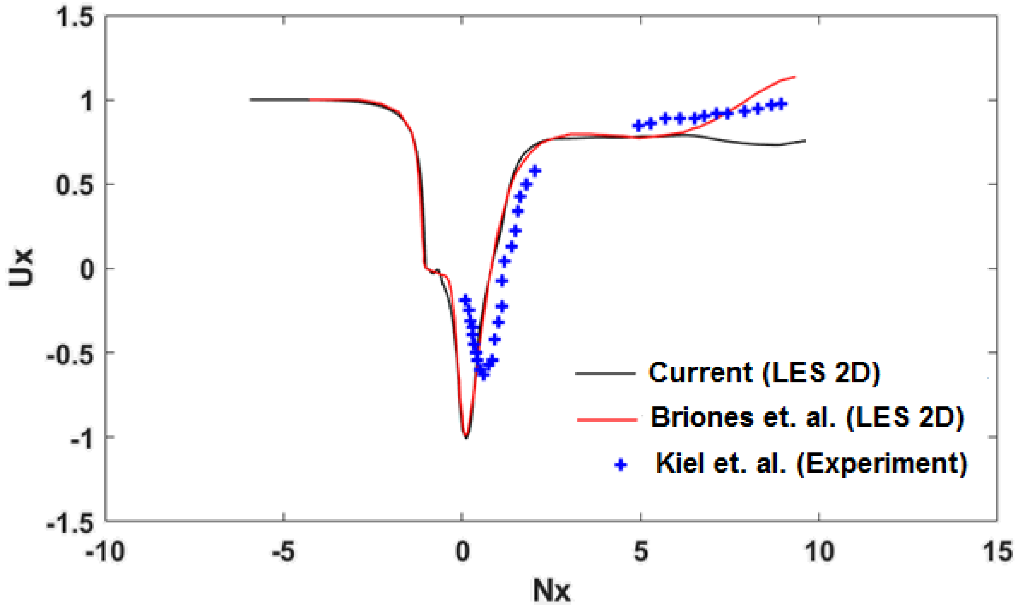

Fig. 5: Comparison of time averaged centerline axial velocity profile for the 2-D case

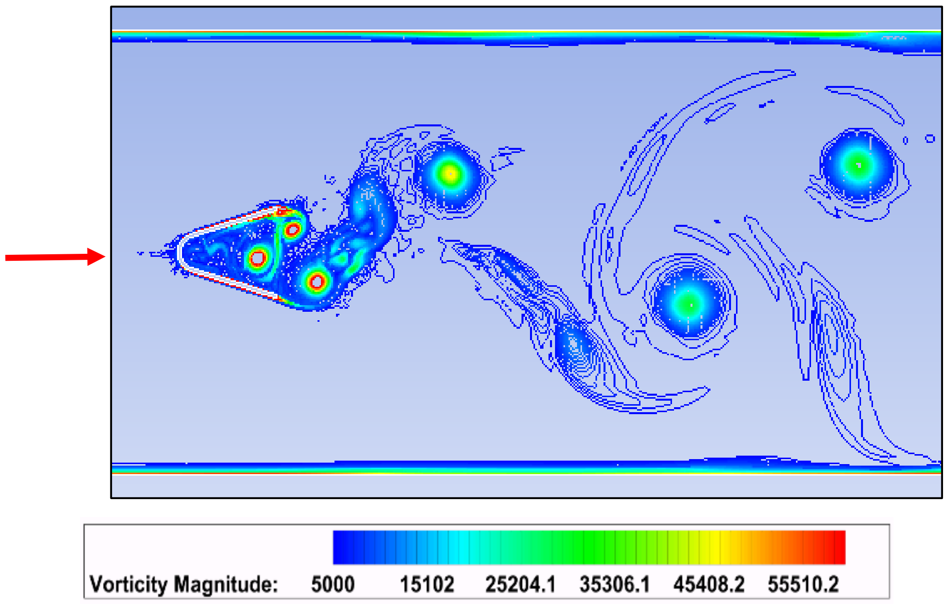

Fig. 6: Instantaneous Vorticity Contour showing vortex shedding for the 2-D case

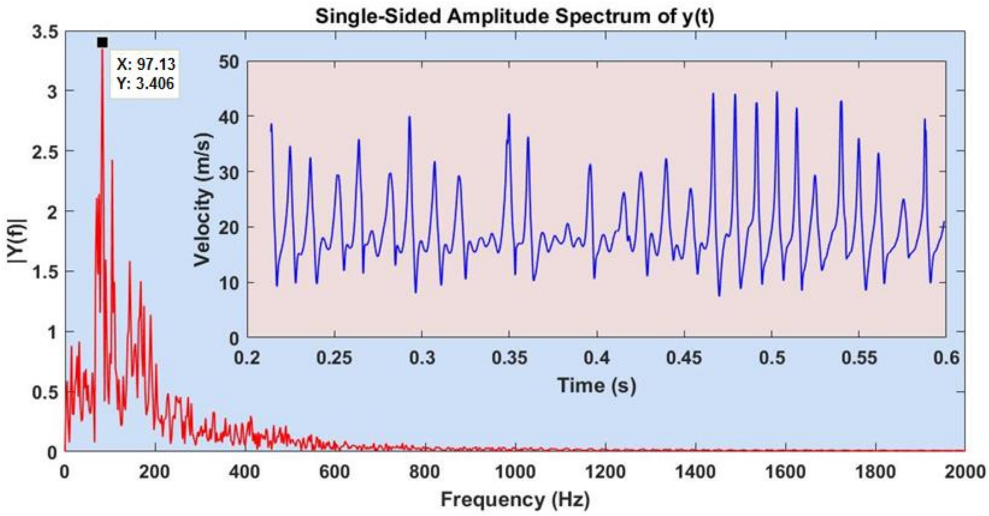

Fig. 7: Time series and FFT of velocity magnitude behind the V-gutter for the 2-D non-reacting case, Inlet velocity = 16.2 m/s

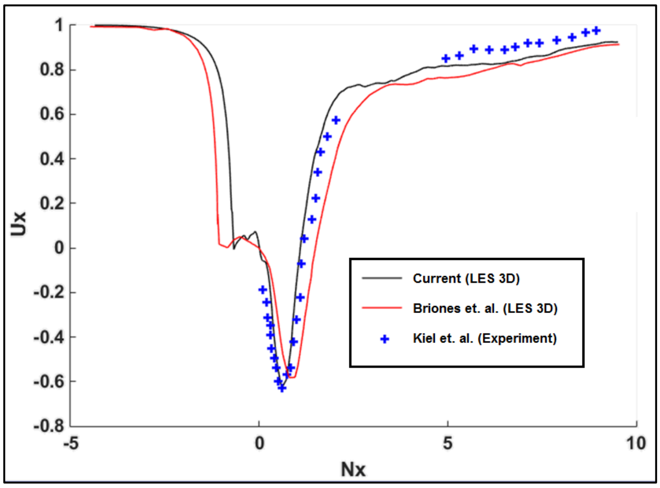

Fig. 8: Comparison of non-dimensional time averaged centerline axial velocity profile for the 3-D case

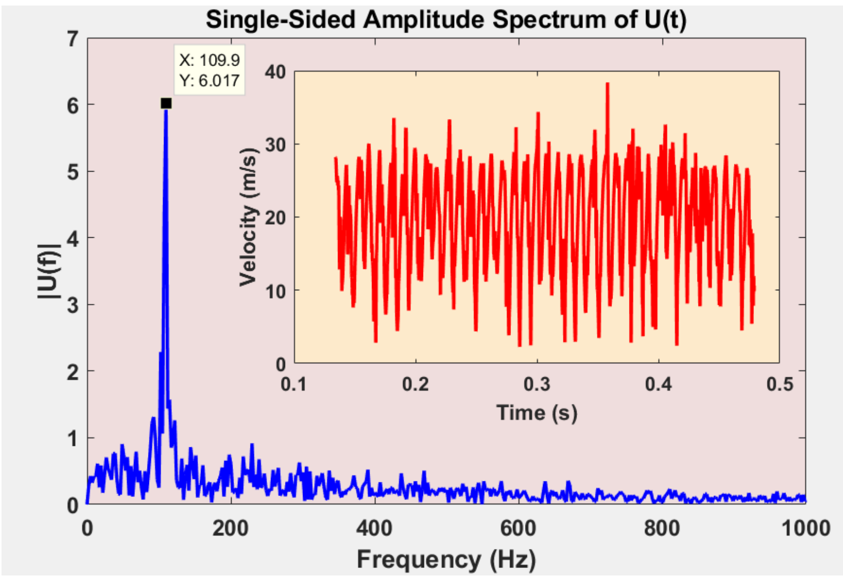

Fig. 9: Time series and FFT of velocity magnitude behind the V-gutter for the 3-D non-reacting case, Inlet velocity = 16.2 m/s

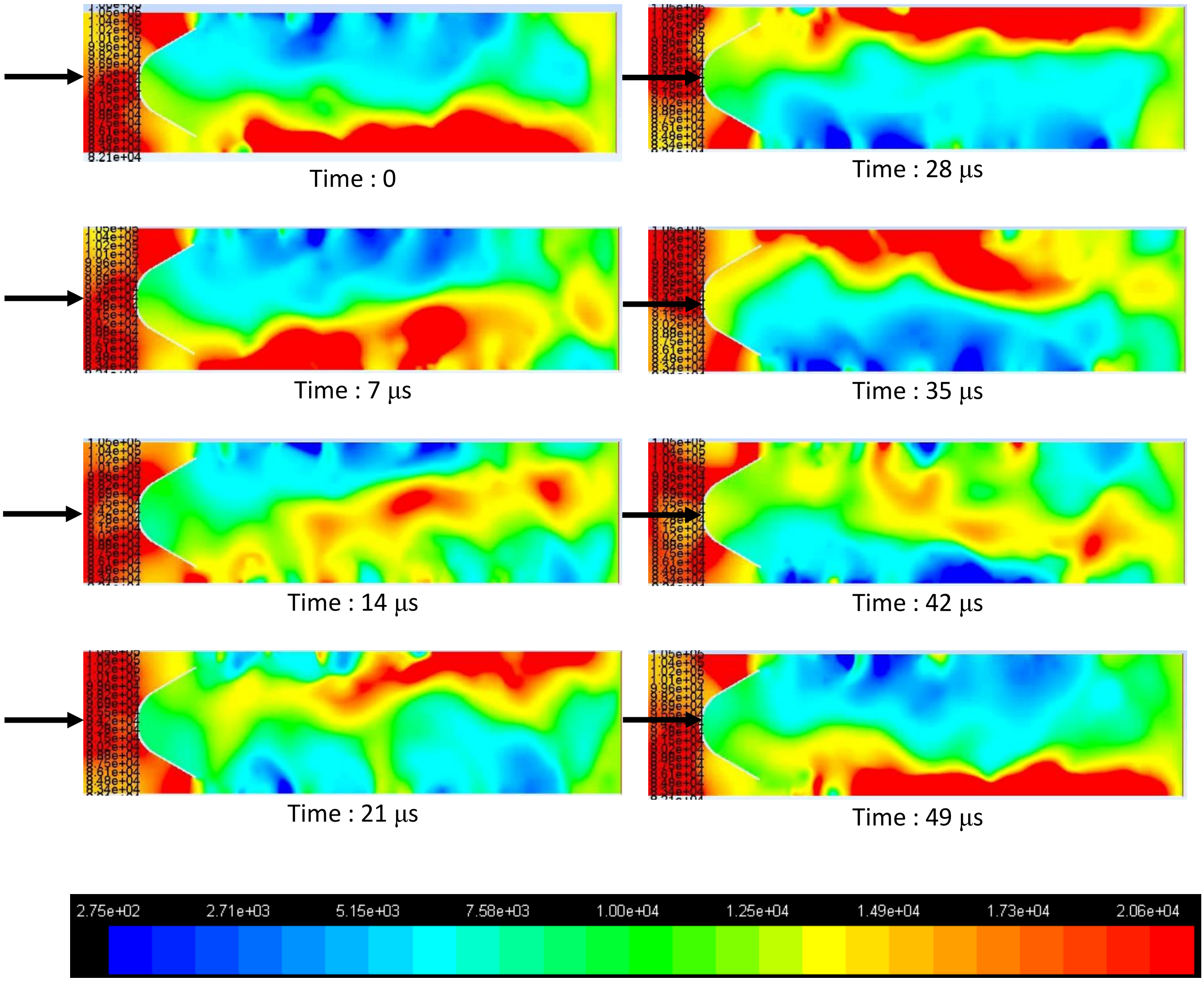

Fig. 10: Transverse Pressure Oscillation showing at differnet time during screech condition

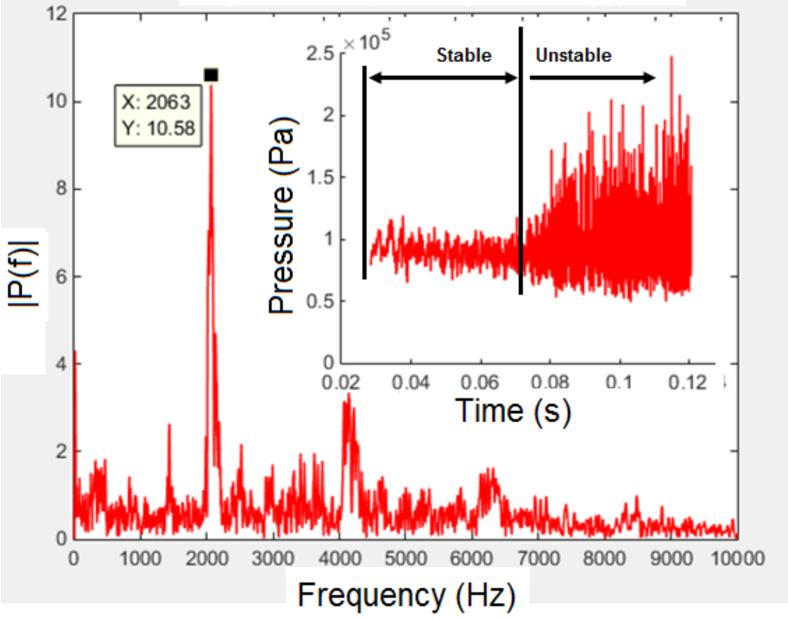

Fig. 11 : Evolution of the absolute pressure oscillation from stable to unstable combustion(LES)

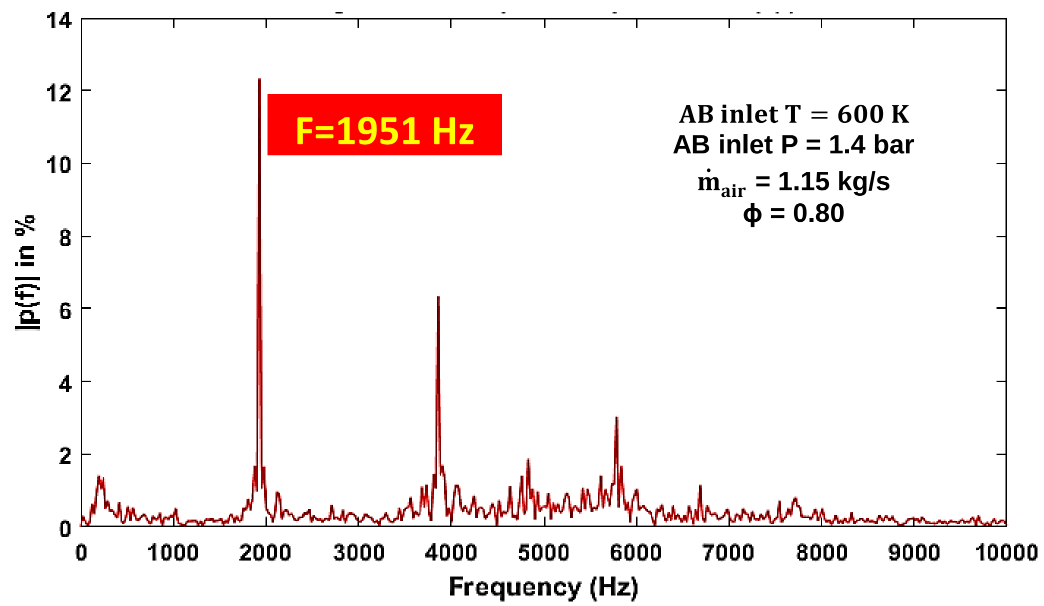

Fig. 12: FFT of the absolute pressure oscillation showing dominant frequency of oscillation (Rajashekar et. al [3])

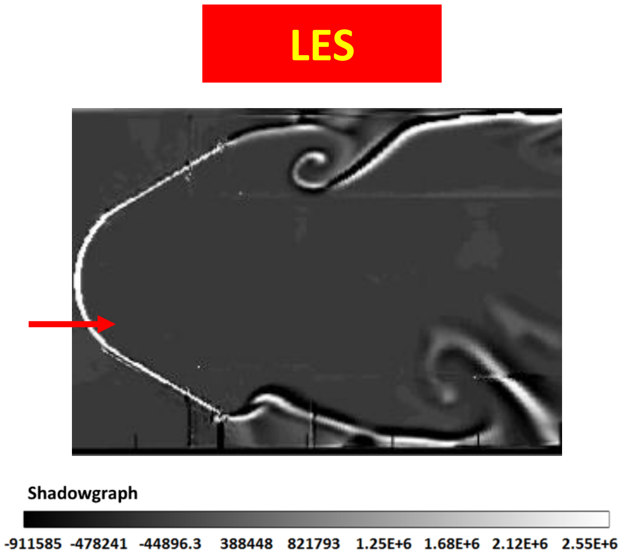

Fig. 13: Numerical shadowgraph showing asymmetric vortex shedding during screech condition (Overall equivalence ratio = 0.8)

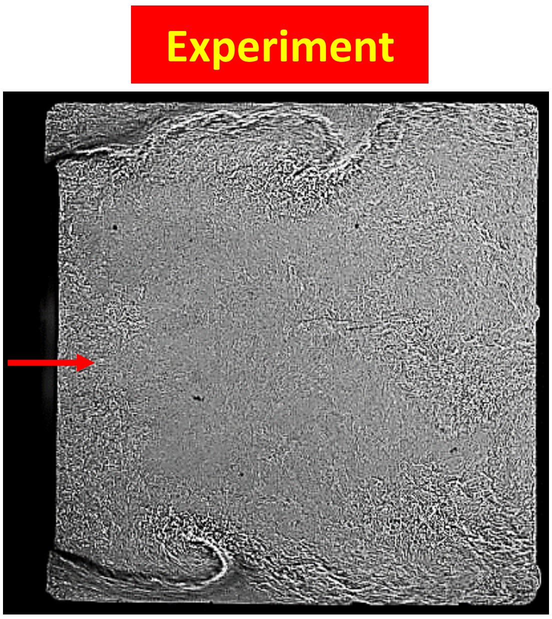

Fig. 14: High-speed shadowgraph flow visualisation of screech combustion instability (Rajashekar et. al [3])

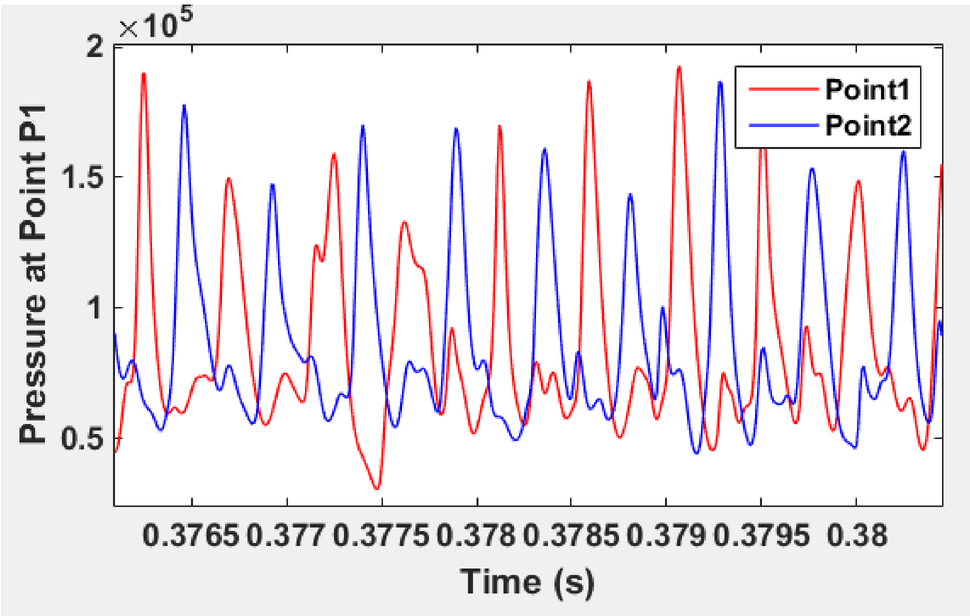

Fig. 15: Comparison of pressure measured (LES) at point 1 (top wall) and point 2 (bottom wall) for reacting flow (Overall equivalence ratio = 0.8)

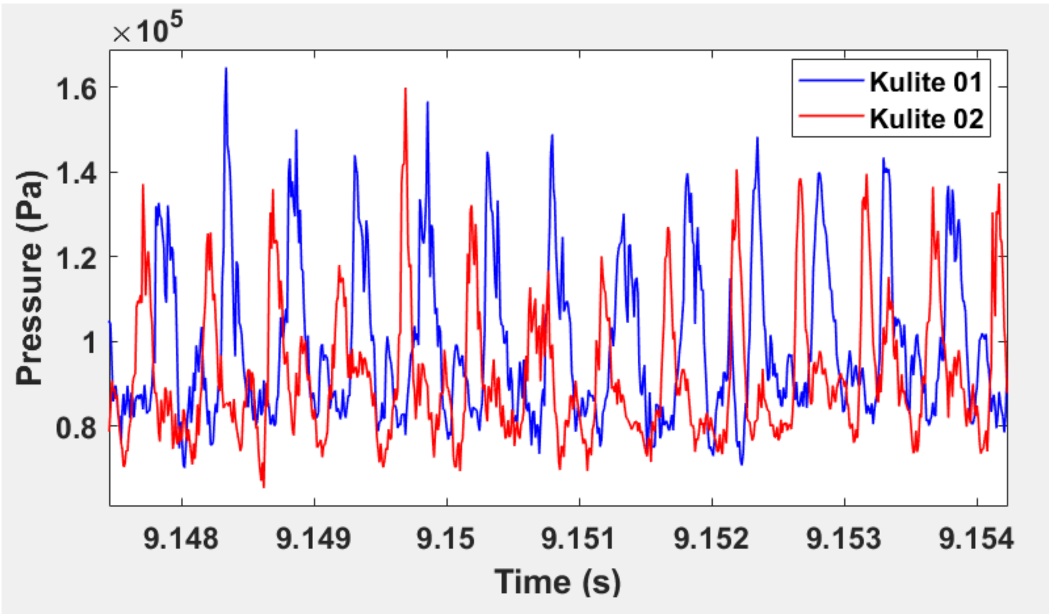

Fig. 16: Comparison of pressure measured at two point (top wall, bottom wall) during experiment (Rajashekar et. al [3])