FDL Research: Present studies and future plans

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CAIPEEX Phase IV

Turbulent Wall Jets

Monsoon low-level jet (MLLJ) is the large scale flow in the atmosphere setup over the Arabian sea and the Indian landmass [1]. The MLLJ has a non-monotone vertical profile of wind speed with the maximum (15-20 m/s), often called the jet core, occurring at the height of 1-1.5 km (~ 850 hPa) from the surface; wind speed decreases on either side of this maximum. It is not unreasonable to expect that the mean vertical profile as well as vertical turbulence structure of MLLJ are similar to other LLJs occurring in different parts of the globe although the reasons for their occurrence could be very different. It has been pointed out that LLJs show remarkable resemblance to laboratory turbulent wall jet flows [2]. Aircraft measurements suggest the presence of elevated turbulence in the outer part of LLJs [3]. This elevated turbulence may alter or interact with the atmospheric boundary layer which is present up to jet core in LLJs. As the structure of laboratory turbulent wall jet is analogous to the structure of LLJs, we are here studying the laboratory turbulent wall jet flow in detail for the better understanding of above said possible interaction in LLJs.

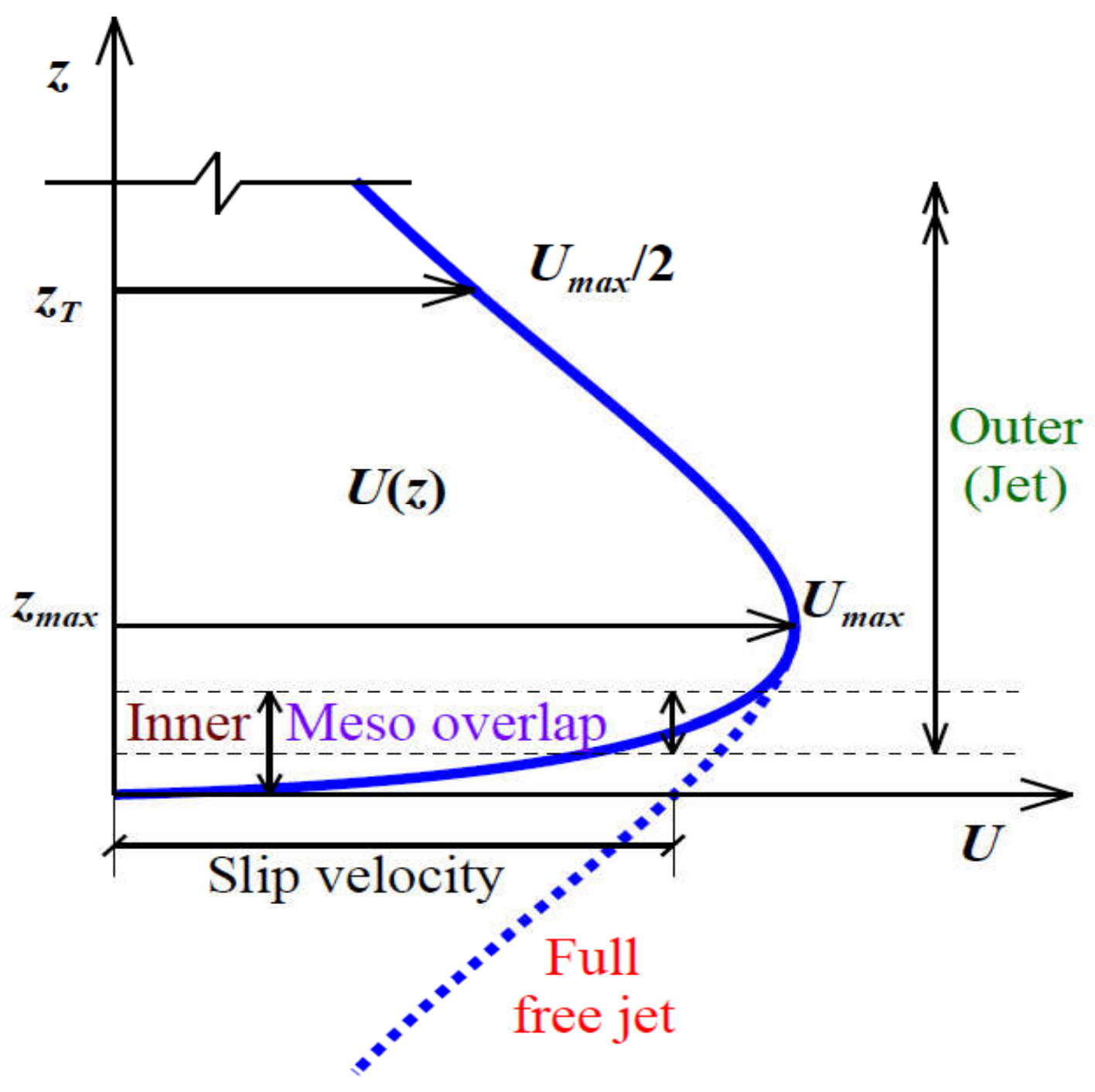

Fig.1 Schematic of the layered structure of wall jet flow

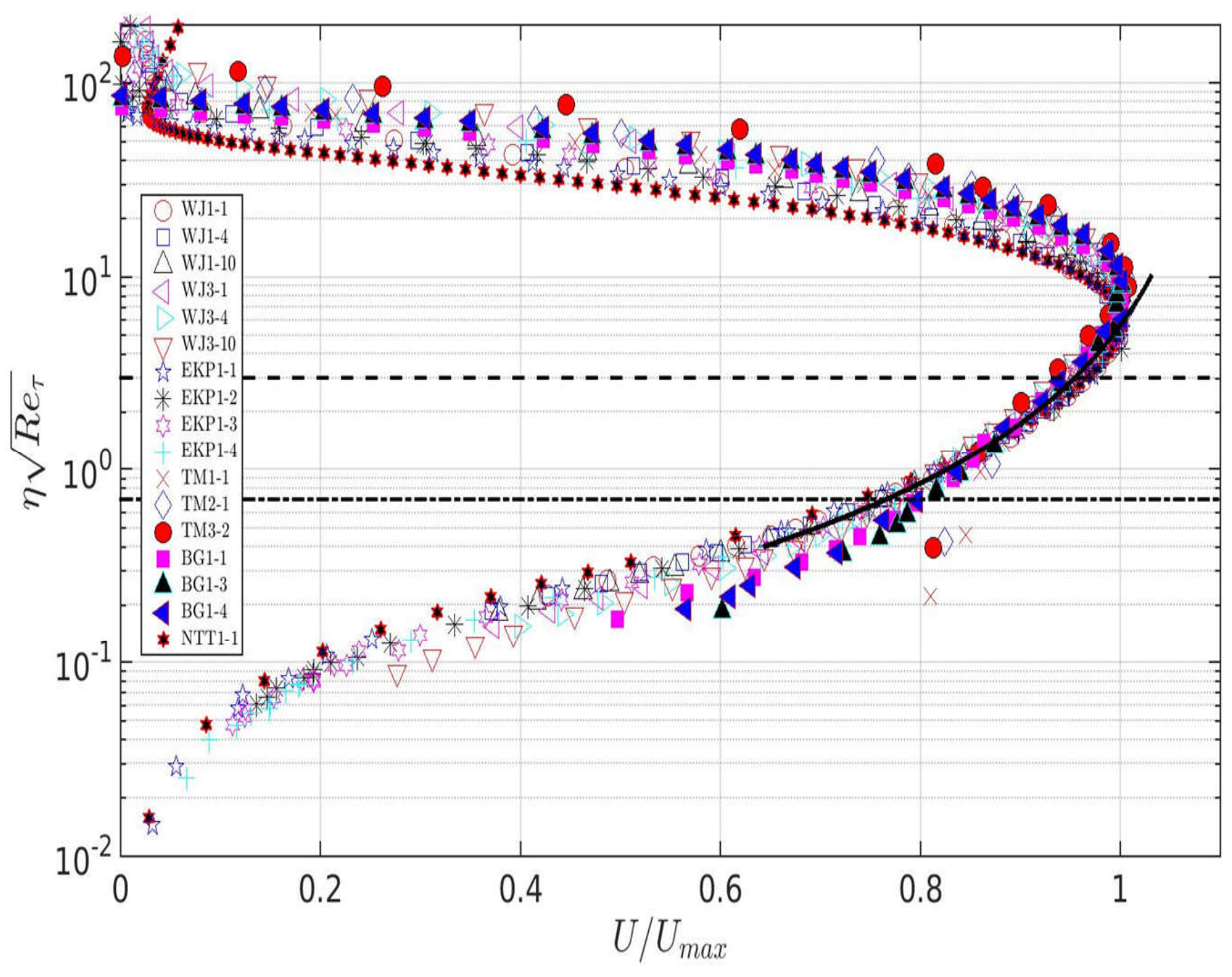

Fig.2 Overlap layer scaling of mean velocity profiles for the wall-jet data sets

For the detailed study of laboratory wall jet, we have developed the setup in the Fluid Dynamics laboratory (FDL) at IITM, Pune. This setup is made up of a flat, straight, polished aluminium test surface, 2 feet wide, 5 feet long and 6 mm in thickness, serves as the test surface along which a two dimensional jet is blown. A speed-controlled blower discharges air flow into a settling chamber which consists of a honeycomb, a set of suitable screens and a well-designed two-dimensional nozzle (width L=300 mm) whose exit slot height b is fixed at 10 mm. Wall shear stress is directly measured using Oil-film interferometry (OFI) [4]. Mean velocity measurements are performed using a Pitot tube (OD of 1.2 mm) and an ethanol-based projection manometer. Turbulence profiles are measured using custom-made hotwire anemometry probes operated with the Streamline Pro system from Dantec Dynamics, Denmark. To get field measurement of the flow we have used Particle image velocimetry (PIV).

From our recent study, it has been observed that the laboratory wall-jet is made up of an inner (wall) layer and an outer (free jet) layer, as shown in Fig 1. The inner part of the wall-jet develops under the influence of the wall and is governed by the inner scales, while the outer part is like a free jet and governed by outer scales. These scalings are universal i.e. independent of Reynolds number. It is also found that, the overlap layer (Meso overlap) in wall jets occur below the velocity maximum as shown in Fig 1. Using the ideas of asymptotic analysis, we have theoretically derived a universal meso overlap velocity profile in terms of an intermediate variable ($\eta\sqrt{Re\tau}$)

$$\frac{U}{U_{max}} = K_o\left(\eta\sqrt{Re_\tau}\right)^A - \frac{\beta}{U_{max}} \qquad \text{……..(1)}$$

where K_0 , A, and β are universal constants; $\eta = z/z_T$ and $Re_\tau = U_\tau * z_T/\upsilon$ (υ is the fluid kinematic viscosity and U_τ is the friction velocity). Figure 2 shows remarkable collapse of all data (our lab data as well as data from the literature) on to a single universal power-law curve (Eq.1) confirming the presence of meso overlap .

A paper titled "Scaling mean velocity in two-dimensional turbulent wall jets" has been recently accepted for publication in the Journal of Fluid Mechanics (Impact Factor 3.17).

Preliminary PIV results

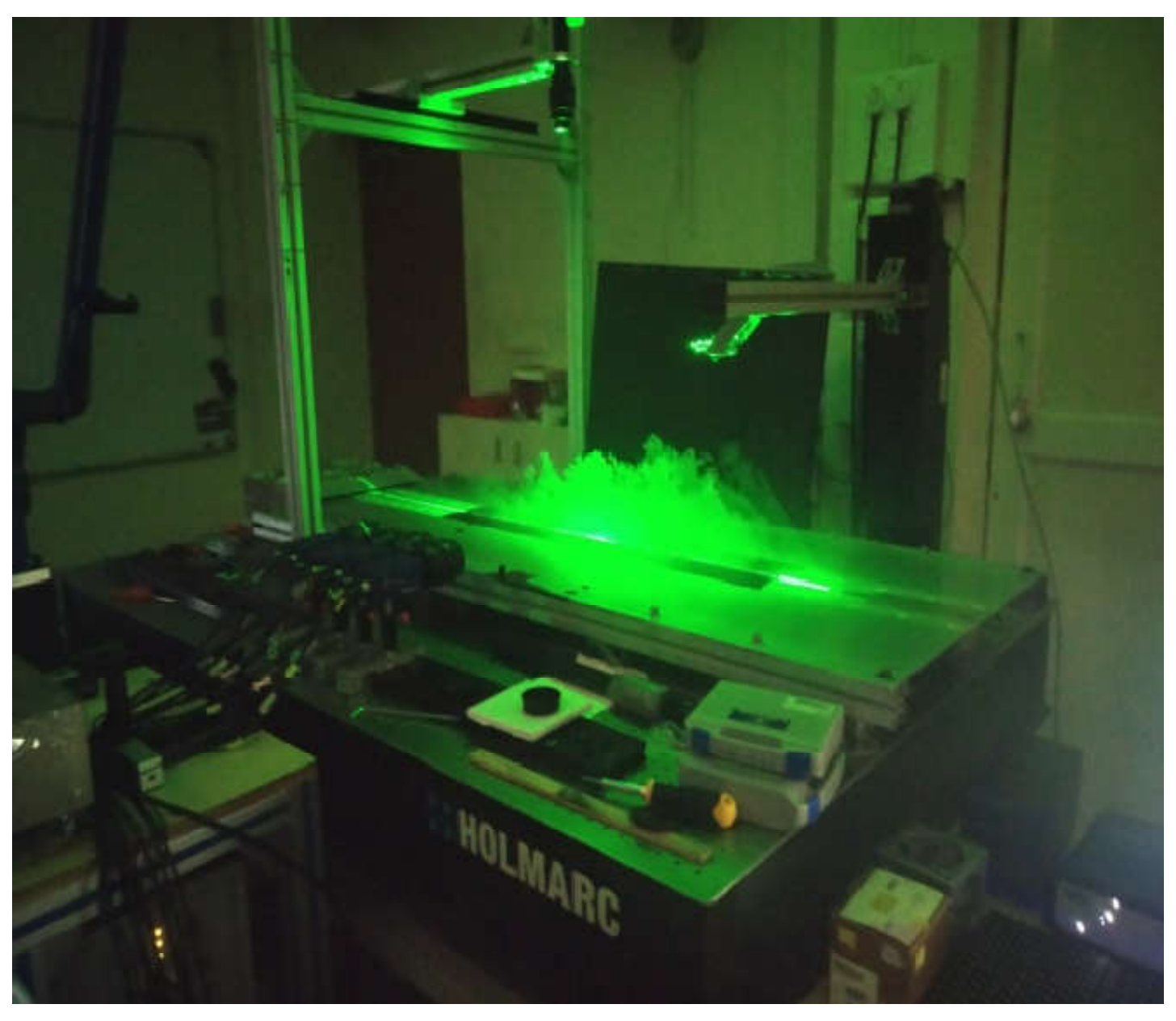

Fig.3 PIV setup for wall jet flow

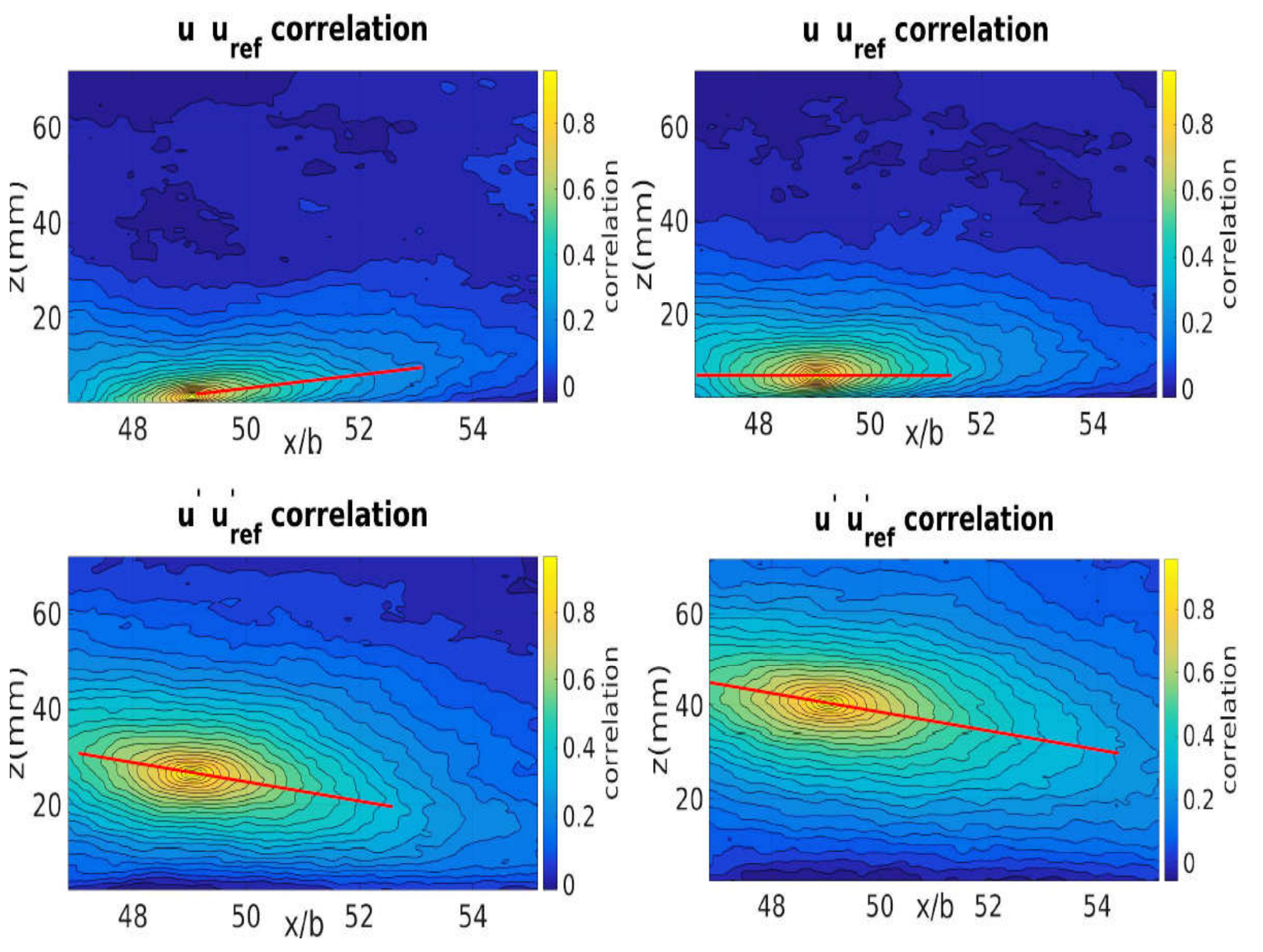

Fig.4 Contour plots of two point correlation of the fluctuating velocity field

PIV is a double-pulsed laser technique used to measure the instantaneous velocity fields by photographically determining the displacement of seeding particles during a short time interval. Unlike other methods such as pitot tube and hot-wire anemometry that measure velocity at a point, PIV provides velocity values simultaneously throughout an entire field-of-view. Figure 3 is a photograph taken during the experiment, showing PIV measurement of wall-jet flow. A smoke machine is used for seeding the flow with droplets of mean diameter of 1-2 micrometers. Instantaneous velocity field data are captured at various blower speeds using DaVis10 software, and further processing is done in MATLAB. Two-point correlation of streamwise fluctuating velocity field is calculated with respect to a reference location (x/b=49.5). Figure 4 shows correlation contour plot of fluctuating velocity (u') field with a reference velocity (u'ref) at different wall-normal locations: counter-gradient diffusion region (z=3mm), mean velocity maximum region (z=6.5mm), mean velocity inflection point (z=25mm), and z_T (z=40mm) respectively. The red line drawn in Fig 4 shows the direction of slowest drop in correlation values indicating the inclination of eddies in the flow. These eddies are forward-leaning in the near-wall region below the velocity maximum, nearly wall-parallel at the velocity maximum, and become backward leaning in the outer part of the wall jet.

Future plans

(A) Convection setup (interacting plumes)

Coalescence of convective plumes is common in atmospheric boundary layers but field measurement of the interaction between these plumes is challenging. These plumes can be simulated in a laboratory by generating turbulent plumes with density difference or temperature gradient. While the interaction and entrainment characteristics of such plumes have been studied in the literature, turbulence characteristics, multi-scale structures and spatial and spectral transfer of TKE are still not well studied. We plan to develop a convection setup to study the mixing, entrainment, and turbulence characteristics of multiple interacting plumes by using PIV and PLIF (Planar laser-induced fluorescence) techniques. This is expected to lead to a better understanding of the physics of plume interactions and development in the atmosphere. Figure 5 shows a schematic of the interaction of two forced buoyant plumes in a linear stratification [5].

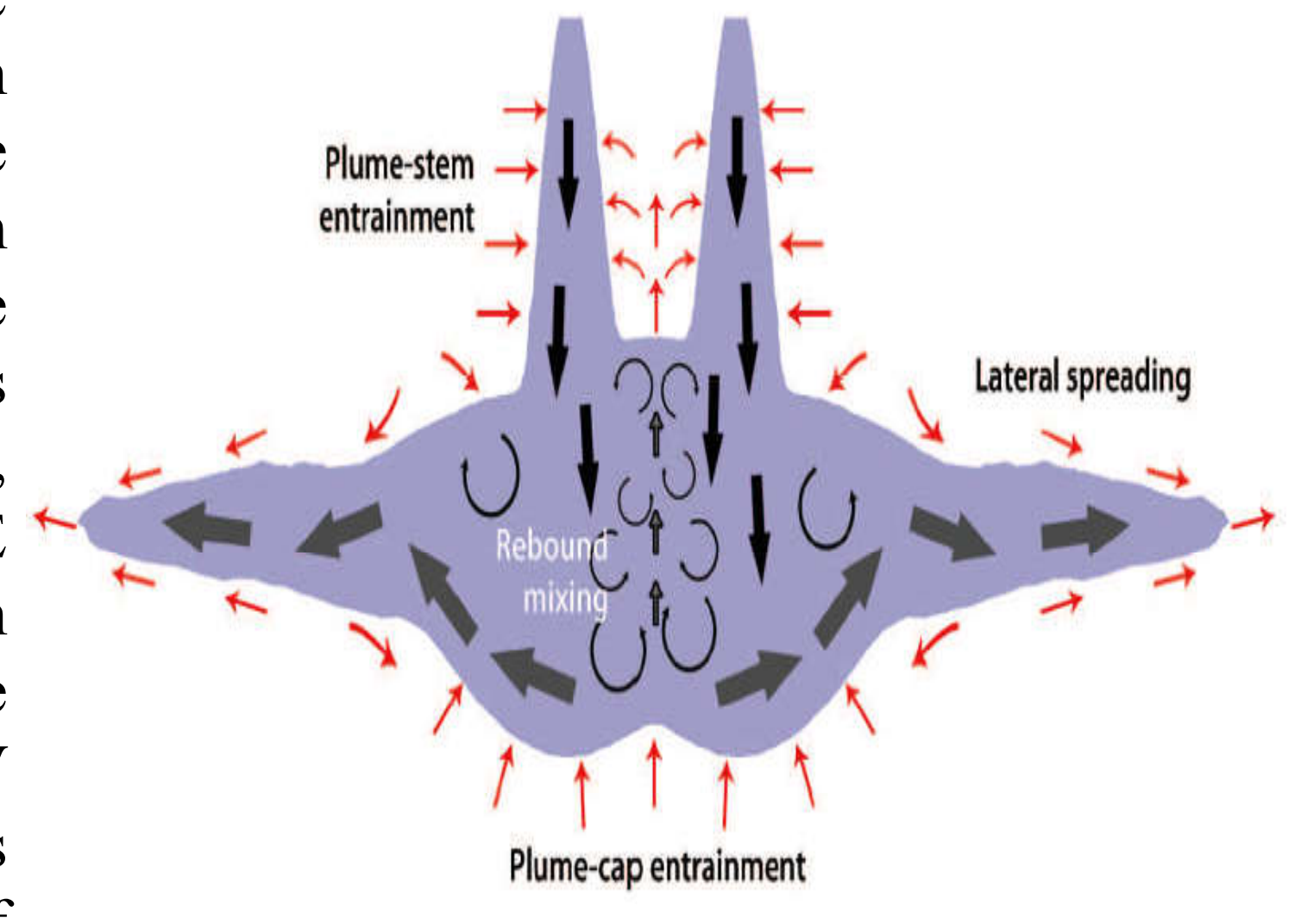

Fig.5 Schematic of the interaction of two buoyant plumes [5]

(B) Cloud chamber (proposed)

Recent research has shown that aerosol and clouds play an important role in regulating the Earth's radiative balance and climate while interacting in a complex manner [6]. Aerosols act as condensation nuclei for water vapour and determine the formation and life cycle of clouds. Turbulence plays a key role in these processes by influencing cloud droplet size distribution, aerosol nucleation, hydration and activation, and spatial segregation. For example, mixing by entrainment of dry air into saturated air at the edges of a cloud is an important and still not fully understood process that requires further laboratory and field studies. Understanding and modelling the complex interactions between aerosols and clouds is challenging due to turbulence-induced water vapour and temperature fluctuations at small spatial (< 100 mm) and temporal (< 10 sec) scales.

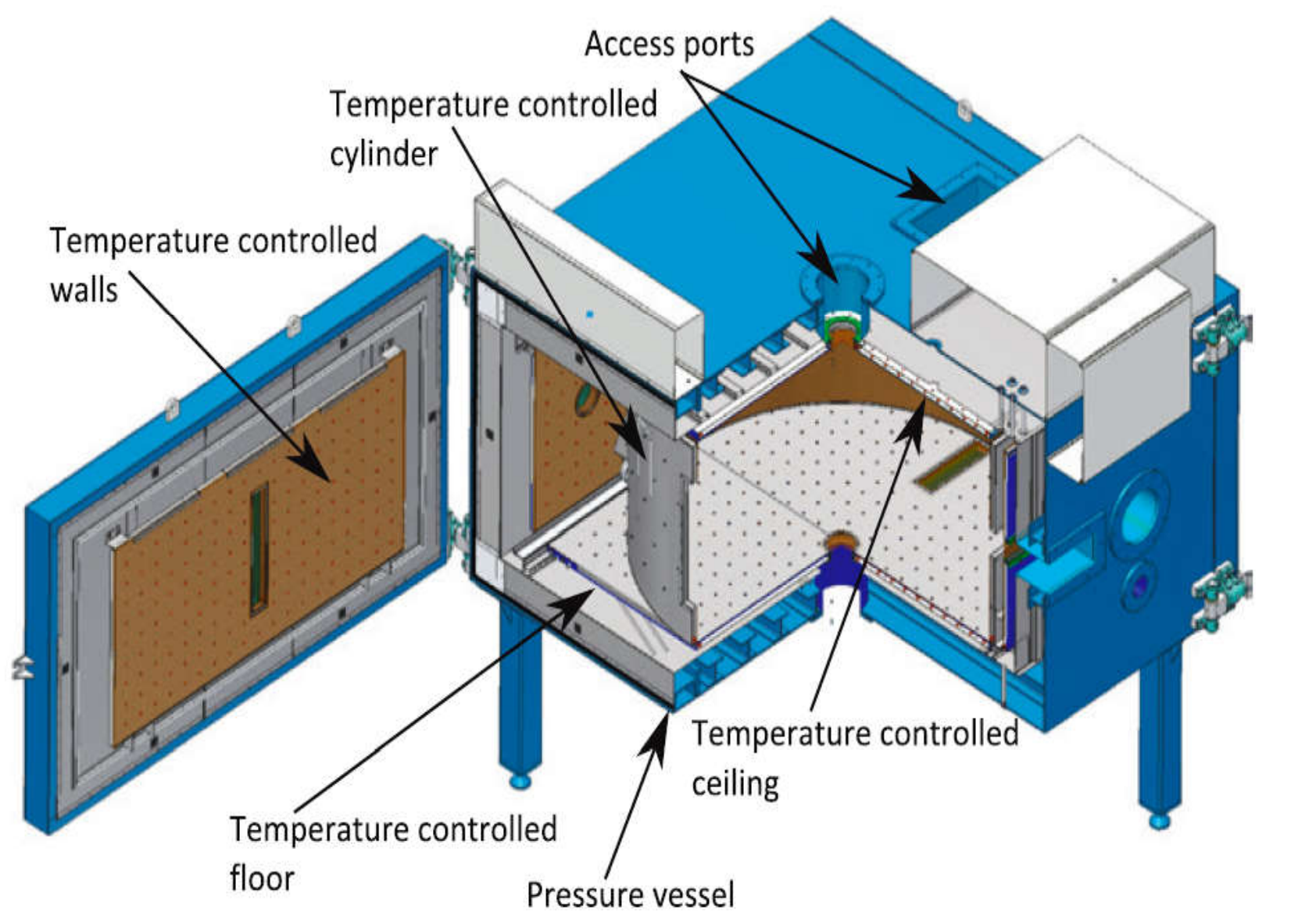

Fig.6 Schematic of an existing cloud chamber at MTU, USA [7]

The research enabled by the newly proposed cloud chamber will help in understanding the intricacies of the interactions between aerosol, clouds, and turbulence and is expected to complement the field measurements of CAIPEEX campaigns. Figure 6 shows a schematic of an existing cloud chamber (the Pi chamber) at MTU, USA [7]. This chamber can be operated in two modes, i.e. expansion cloud and steady-state turbulent mixing cloud. In expansion cloud mode, the enclosed mixture of air and water vapour is adiabatically expanded to locally reduce the air temperature, thereby generating supersaturated conditions and inducing water vapour to form cloud droplets on any cloud condensation nuclei (CCN) present in the air. This mode mimics natural process, although the presence of walls inevitably limits the time up to which adiabatic conditions can be maintained. The second mode of mixing cloud is created by setting up turbulent moist Rayleigh- Benard convection. In this type of cloud formation, warm saturated air originating at the bottom surfaces mixes with cold, saturated air originating at the top surface [7].

(C) LES and DNS studies

Indian monsoon features a persistent and strong low-level-jet (LLJ) that occurs as a result of the atmospheric large-scale circulation. Thus, LLJ is a shear-dominated monsoonal phenomenon that is crucial to the transport of energy, momentum and moisture from surface to the free atmosphere. Also due to strong shear above as well as below the wind speed maximum, turbulent mixing and transport are expected to be strong throughout the vertical extent of the LLJ. While the thermal boundary layer (well-mixed layer) is seen to extend up to the LLJ core, the shear-driven (jet) turbulence above the jet core could possibly interact with the thermal/shear generated turbulence in the boundary layer. Such an interaction could modulate the turbulence structure of the mixed layer altering the fluxes of momentum and heat into the free atmosphere. The situation is expected to get even more complicated with the in-cloud turbulence interacting with the jet and/or mixed layer turbulence. As mentioned before, we have already started simulating the basic shear-driven wall-bounded jet's turbulence properties in a laboratory wall-jet setup to examine the interaction of the jet and near-wall turbulence. Next, to gain further insight into these problems, we are in the process of setting up a large eddy simulation (LES) of MLLJ without and with the effect of clouds. We are also in the process of setting up a Direct Numerical Simulation of our laboratory wall jet flow.

Acknowledgements

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