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TURBULENT PREMIXED FLAMES IN MICROGRAVITY

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1. Introduction

This report summarizes the progress made under this project in the last year. Both the numerical and experimental studies are discussed below. Further details (when relevant) are provided in the attached Appendix.

2. Experimental Progress

The experimental cold-flow facility is now full operational and is currently being used to obtain baseline turbulence data in a Couette flow. The baseline turbulence data is necessary to confirm the capability of the chosen device to generate and maintain the required turbulence intensity. Subsequent reacting flow studies will assume that a similar turbulent flow field exists ahead of the premixed flame. Some modifications and refinements had to be made to enable accurate measurements. Figure 1 shows the experimental device in its present state. It consists of two rollers, one (driven by a motor) which drives a continuous belt and four smaller rollers used to set the belt spacing and tension to minimize belt flutter. The entire assemble is enclosed in a structure that has the dimensions to enable future drop tower experiments of the hot facility. All critical dimensions are the same as the original plans except for the pulley ratio which has been changed to enable a wider operating regime in terms of the Reynolds number. With the current setup, Reynolds numbers as low as 100 and as high as 14,000 can be achieved. This is because the in-between belt spacing can be varied from 1 cm to 7.6 cm, and the belt speed can be accurately varied from .15 m/sec to 3.1 m/sec.

2.1 Flow-field velocity measurements

Flow field velocity measurement are being performed to determine the turbulence characteristics of this facility and to resolve all foreseeable problems. The knowledge gained from these tests will help us in the design of the hot flow facility and in the design of the experiments that will take place in the hot flow facility. Primarily, the turbulence velocity fluctuations are being measured to determine the mean and fluctuating velocity fields. This is considered essential since this facility is much smaller than the Couette flow facilities that have been employed by other researchers in the past and no data exists for small facilities such as the present one. A well defined turbulence field has to be maintained in this facility in order to study the characteristics of turbulent premixed flame in the next phase. Propagation of the premixed flame into a well established turbulence field is of interest and it is expected that the turbulence characteristics in the hot flow facility will be essentially similar to the turbulence in the present device.

The velocity measurements are being carried out using a TSI system 9100-7 two component laser Doppler velocimeter (LDV). It is worth noting that this approach is also novel since all past studies in Couette flow have employed hot-wire anemometry and the present study is the first attempt to use LDV for velocity measurements in this flow. The present LDV system uses the 488nm and the 514.5nm wavelengths of an Ar^+ ion laser to be measure two velocity components. The probe volume diameter is approximately 0.1 mm, which provides good resolution for the present experiment, even with a belt spacing of 1 cm. The positioning system moves in steps of .004 mm, thereby, enabling adequate resolution of the velocity profile.

Some initial setup effort was involved in getting this system operational. Primarily, the data acquisition system (specially the computer) had to be completely updated/replaced since the original system employed a very old HP system. The current system employs a Pentium PC with new software/hardware. Additional effort was required to clean and properly align the LDV's transmitting and receiving optics. Preliminary tests of the system were carried out by measuring the velocity of seed particles in a free jet. When the system was used for measurements in the Couette facility, it soon became apparent that some modifications to the facility were needed to obtain reliable LDV data. These modifications involved replacing the original Plexiglass sidewalls with glass windows (Fig. 1 note: 6). The windows were necessary because the Plexiglas's light absorbing property resulted in the attenuation of the beams coming into the device, and, in the attenuation of the probe volume's emitted light coming out of the box, the latter being the most crucial.

Another issue that had to be resolved was how to introduce the seeding particle: TiO_2. Several seders were tried. The first seder employed a seder-jet in-between the (belt) sheets. The jet was turned on and seed particles were introduced into the flow; the jet was turned off and then, the flow was left to stabilize. After a certain time, data could be collected. Because of the frequent need for seeding, a second seder was designed. The seder, shown in the Fig. 1 (Fig. 1 - 7), is yet another version, and, is currently in use. This design was adopted because by jetting seed particles around the sheet (rather than directly in-between the belt) only the smaller particles gets entrained in the flow between the rotating belt (this is preferable). Also, by using the jet to introduce the particles around the sheet, the amount of seed particles that deposits on the inside surface of the belt was reduced significantly, thereby, allowing an easier and faster cleanup. Seeding is still an issue which has not been completely resolved and will be studied further.

A significant amount of time was required to fine-tune the system to get the best signal and to diminish the noise. During this period, the TSI-1998 counters were used to analyze the analog signal, but because of electronic problems they have now been replaced by new signal burst correlators (IF-750). In addition to solving the electronics problems, these new correlators have the advantage of using state-of-the-art autocorrelators to determine and validate the measured frequencies, compared to the older amplitude-based technology used by the TSI counters. Thus, the new correlators provide more reliable data and a much higher data rate. After making sure that the results were repeatable, the flow field in the Couette flow facility was studied to determine if the flow-field is two-dimensional in the spanwise direction. As can be seen from Fig. 2, the flow is nearly two-dimensional up to about 1cm to 2cm from the edge of the belt. This test was performed with a 1 cm belt spacing, and will be re-performed with other belt spacing as needed. The advantage of the apparent two-dimensionality is that extensive spanwise measurements need not be carried out and the measurements can be focused within the central portion of the flow field.

For a belt spacing of 1cm and a belt velocity of 1.4 m/sec, a Reynolds number (based on the belt spacing and belt velocity) of around 1000 could be obtained. At this Reynolds number, the mean axial velocity profile deviates from the linear laminar profile, and becomes similar to the fully turbulent profile, as shown in Fig. 3a. But the root-mean-square velocity profile (Fig. 3b) did not show the well known near-wall rms-peak feature seen in previous studies. This suggested that the Reynolds number needs to be increased, not by increasing the belt spacing but by increasing the belt velocity. This has the added advantage of increasing the peak rms turbulence intensity which in turn would allow characterization of a more turbulent field. [This is particularly relevant for the hot flow studies since we are interested in studying premixed flame propagation over a range of u'/S. Here, u' is the turbulence intensity and S is the laminar flame speed. To increase the belt speed, the pulley ratio was increased to more than double the maximum operational belt speed to 3.1 m/sec compared to the earlier maximum of 1.43 m/sec. Mean and rms velocity profiles at this new belt speed are shown in Fig. 4a, and Fig. 4b. It can be clearly seen that not only is the mean profile exhibiting the expected turbulent profile, but also the rms peaks can be clearly seen to occur near the wall. Analysis of the results showed that the present study is predicting a much higher value when compared to data presented earlier by other researchers (in much larger facilities). This might be due to the differences in the scale of the facilities and also, perhaps due to the small 1cm belt spacing used here. [The primary reason for studying such a small spacing is for the future hot experiments since a small spacing would reduce the total amount of premixed mixture in the combustion region]. Additional experiments are planned for the near future to investigate the turbulence characteristics in a flow with a larger belt spacing.

During the experiments summarized in Figs. 3 and 4, certain characteristics of the setup were discovered, which will have to closely monitored in the future. These are due to seeding and belt vibration problems. The seeding process was improved by placing the seder in the present location (see Fig. 1) so that only smaller particles are entrained in-between the sheets. Bigger particles were found to lower rms velocity readings since they cannot follow the flow properly. Seeding is also an issue when trying to determine how many samples are needed to get repeatable data. In the present setup, it was determined that 50,000 points were needed when the data rate was around 2,000 Hz to 1,000 Hz. It was also determined that, at higher data rate, more data points are needed. We plan to address this issue further in the next phase of this study.

The effect of belt vibration was noticed when it was observed that the rms data was repeatable with the same belt, but sometimes changed in magnitude when the belt was changed. This was only noticed when the belt speed was increased and observation suggests that the belt was more prone to braking at higher belt speeds. Each time a belt was replaced, a given condition was re-tested and it was found that even though the mean velocity profiles matched, the rms profiles varied in magnitude, but not in trend. Fortunately, all of the data needed for Reynolds number comparison (discussed above), was taken with the same belt. It is believed that the tension in the belt affects the frequency of vibration which in turn affects the frequency of velocity oscillation. Test are planned to see if tension variation in the same belt is the real cause or if it is a material/fabrication problem. For example, it is not yet clear if the small ridge formed when the Mylar sheet is glued together is causing any perturbation in the flow, specially when the belt spacing is around 1 cm. Increasing the belt spacing should help understand if this is an issue of concern. Fortunately, the experimental device has two tension adjusting screws used to compensate for belt drifting (see Fig. 1 - 5) which we plan to use to study the effect of belt tension. Another possible solution is to put glass plates on both sides of the belt (as done by earlier researchers) to keep the belt from vibrating. But this would hinder the already difficult LDV measurements in the transverse direction and is not considered the best option at present.

2.2 Visualization

Acetone PLIF will be used as a tracer to study turbulent diffusion of passive species in the cold flow device. Although this is not directly relevant to the premixed combustion study, the characterization of the diffusion front would allow us to obtain new and interesting information on scalar diffusion, an area of study that is also of considerable interest. In addition, images of the turbulent diffusion front will enable us to determine the resolution requirements to resolve a wrinkled front in a given turbulent field. Therefore, an experiment using acetone PLIF is being setup. A tunable Lambda Physik excimer laser will be used to produce a laser pulse at a wavelength of 248nm and used to excite acetone vapor which will fluoresce broad band in the blue (350-550nm), with peaks at 445nm and 480nm. An Kodak Ektapro 1012 intensified, digital, high speed camera will be used to collect pictures of the scalar (acetone) field.

It has been determined that some modifications to the experimental device are needed to enable acetone PLIF measurements. This is due to the fact that Mylar belt fluoresces, and thus, also absorbs the UV radiation produced by the excimer laser. Thus, a longitudinal sheet perpendicular to the Mylar sheets cannot be positioned in the experimental device by shining it through the belt. To avoid the belt, the UV beam needs to shined in-between the belt sheets. This leads to the addition of the mirror holding system (Fig. 1 - 8 and 9), and a cut-through in the side of the device's structure (see Fig. 1 - 10). These changes have been carried out so that the sheet is shined into the side of the apparatus, through the cut-through, and then get turned 90° by the mirror to produce a beam perpendicular to the Mylar sheet in the longitudinal direction.

The process of acetone seeding is also being investigated. The approach currently being tested is to position a droplet at the end of a hypodermic needle in the middle of the flow-field. The droplet should rapidly evaporate due to the shear in the flow, and the resulting gas could be tracked due to their fluorescence. Another possible approach would be to introduce the acetone already in a gas form. An interesting location for acetone introduction, is at one or at both of the re-circulating regions located at the end of the experimental device. This would allow us to determine how this region in the device interacts with the flow-field itself, and how much attention should be paid to it when designing the hot flow facility.

Preliminary work on the planar laser induced fluorescence (PLIF) is nearing completion. Two mockups were built to check the feasibility of PLIF inside the experimental device. The tests with the chosen alignment of the laser beam (with respect to the Mylar sheet) have shown that it is possible to obtain reliable data from these experiments.

A new seeding technique consisting of flow tagging with phosphorescent particles (ZnS: Cu, Al) is also going to be tried. In this approach, a point, line, or sheet of particles is created and then the evolution of this sheet is tracked in the flow. In this case, the phosphorescent particles will be excited with an Ar^+ beam for a short period of time. The particles will then be tracked due to their phosphorescence. This will give us more insight on the turbulent structures in this flow field. For example, numerical studies have revealed the presence of turbulent burst regions very close to the wall which is a cause of the rms velocity peak near the wall. It is hoped that this technique will also enable to help determine some of the belt effects.

Acetone PLIF and flow tagging studies are expected to be completed in the first half of the next year's research program.

2.3 Stationary Turbulent Premixed Combustion

Although the reacting Couette flow facility is not yet ready, the issues related to flame visualization and safety needs to be addressed now. Therefore, we are currently constructing a simplified hot facility that has the dimensions identical to the Couette flow facility but does not involve any moving parts such as the rotating belt. Therefore, this device in its baseline state mimics a constant volume bomb that has been used in the past to study premixed flame speeds. It consists of a closed box with quartz windows for flow visualization. However, unlike the earlier devices, this test chamber will include a mechanism to introduce small-scale turbulence (without any mean shear, since there is no moving belt). To mimic the effect of turbulence, this device contains a stirrer that will stir the premixed mixture at a specified rate and essentially will mimic a forced isotropic turbulence (albeit, with some wall effects). The goal of this study is to determine how the flame will develop in this domain (in a stationary mixture, the laminar flame propagation will result in the famous "tulip" flame that has been studied in the past). Here, our interest is to determine the behavior of the flame in a constantly stirred turbulent fluid. Flow visualization will be used. In addition, this facility will allow us to determine the safety methods to either vent the mixture or introduce inert gas to stop the combustion as and when required. Additional issues such as the temperature of the walls, pressure rise and flame front distribution will be determined in this facility. The construction of this facility has already begun and we expect to begin some experiments next quarter.

3. Numerical Studies

The numerical study has made significant progress. We have validated the baseline LES against available experimental data (for Reynolds number quite similar to our facility). The numerical model has been shown to be capable of reproducing both the mean turbulent velocity and the turbulence intensity quite accurately. Some results are presented in Figures 5a-d which show the comparison of the LES and DNS predictions with experimental data. Subsequent to this study, the simulation model was used to study the propagation of a thin premixed flame front using both the DNS field and the LES method. At present, no heat release is included (and hence there is no gravity effects). The premixed mixture was ignited at the central location as a small burned source and the propagation of the flame front was modeled using the G-equation model. This model considers the flame as a thin interface that is convected by the fluid velocity and propagates normal to itself at the local flame propagation velocity. The propagation velocity is the laminar flame speed for laminar flow but for turbulent flow, this speed is unknown, and, needs to be modeled. The method using the G-equation is our principal focus since, this approach avoids the need to include detailed finite-rate kinetics into the simulation model and thus, reduces the computational cost significantly. The effect of finite-rate kinetics is implicitly included in the specification of the laminar flame speed and the effect of heat release is included by properly specifying the total enthalpy of the mixture (which includes the heat of formation). We do plan to include finite-rate kinetics into the simulation by incorporating global reaction mechanisms at a later stage.

In the present study (so far), two approaches are being used. (1) The DNS velocity field is used to simulate the propagation of the thin flame front with the laminar flame speed. Since in this case, the turbulence is fully resolved, the effect of turbulence on the flame front (wrinkling etc.) can be used to estimate the "turbulent" flame speed. (Note that this approach is not feasible for the heat release case). (2) The second approach is the LES approach in which the G-equation is solved within the subgrid using the linear-eddy model and the propagation of the flame front is estimated from the resolved G-field. Again, in this approach, the subgrid domain is considered fully resolved and therefore, locally, the flame speed can be specified as the laminar flame speed and the results of the simulation can be used to determine the turbulent flame speed. This particular approach is the basis of the numerical research and is currently still underway.

Results (Figure 6 - Color plot shows the temporal evolution of the flame ball in a stationary state turbulent Couette flow) show that as the flame front grows, it initially becomes a skewed flame ball (skewed due to the mean shear). However, at later times, the flame ball begins to twist and eventually tear-off into small flame structures. This tearing phenomena is shown in this figure. However, since no heat release is yet included, this phenomena cannot be considered a local flame extinction process. Flame breakup and local extinction or wall-quenching are issues that will be considered in the next quarter. Results of these studies will be reported soon.

4. Plans for the coming year

4.1 Experimental

The experimental study will further investigate the velocity field in the test facility for a range of Reynolds number. Both the belt spacing and the belt velocity will be changed to vary the Reynolds number. Issues related to the belt effects (tension and vibration) will be evaluated first during this study. Tension/belt effects must be determined before any more data can be taken. A study of Reynolds number effects due to changes in both belt speed and belt spacing will then be possible. Subsequently data will be obtained for both the longitudinal and transverse velocity field and also on axial two-point correlation's. This set of data should establish the properties of the test facility in enough detail to consider the cold flow measurements complete. Flow visualization will then be carried, initially using the phosphorescent visualization technique. Then the acetone PLIF will be used in the experimental device itself.

The static hot facility should become operational sometime in the next few months and will be utilized to investigate premixed flame propagation in a isotropic turbulent field. Various fuel-air mixtures at different equivalence ratios are planned for this study. As mentioned above, the principle focus of this study is to determine how to ignite and extinguish the combustion process in the device. Methods that are safe and automatic will be investigated. The propagation characteristics of the premixed flame will be visualized in this device. Since, with heat release, the effect of buoyancy can become dominant, comparison with numerical simulations will be carried out to identify the characteristic features. These studies (both the cold flow and static hot flow) should provide us with sufficient information to begin the construction of the hot flow facility (which is slated to begin in the second or third quarter of next year.

4.2 Numerical Studies

The numerical studies will continue to explore the effect of gravity on the premixed flame propagation characteristics. The subgrid model for combustion should become validated by the second quarter of the next year and subsequently, will be utilized to simulate various types of premixed flames in a stationary turbulent Couette flow. Since the LES methodology for this phase involves significantly new model development some effort will also be directed to validate the subgrid premixed combustion model using simplified flows. In addition, since this numerical approach is only optimal on massively parallel processing systems, a parallel version is currently being developed for future studies.

Publications

Menon , S. (1996) "Parallel Simulations of Unsteady Turbulent Flames" to be presented at the 1996 EUROSIM International Conference: HPCN Challenges in Telecomp and Telecom: Parallel Simulations of Complex Systems and Large-Scale Applications, Delft, The Netherlands, June 10-12, 1996; also to appear in the Proceedings.

Menon, S. (1996)"Large-Eddy Simulations of Turbulent Premixed Flames in Couette Flow", AIAA Paper No. 96-3077, to be presented at the 32nd AIAA/ASME/ASEE/SAE Joint Propulsion Conference, Orlando, Fl., July 1-3.

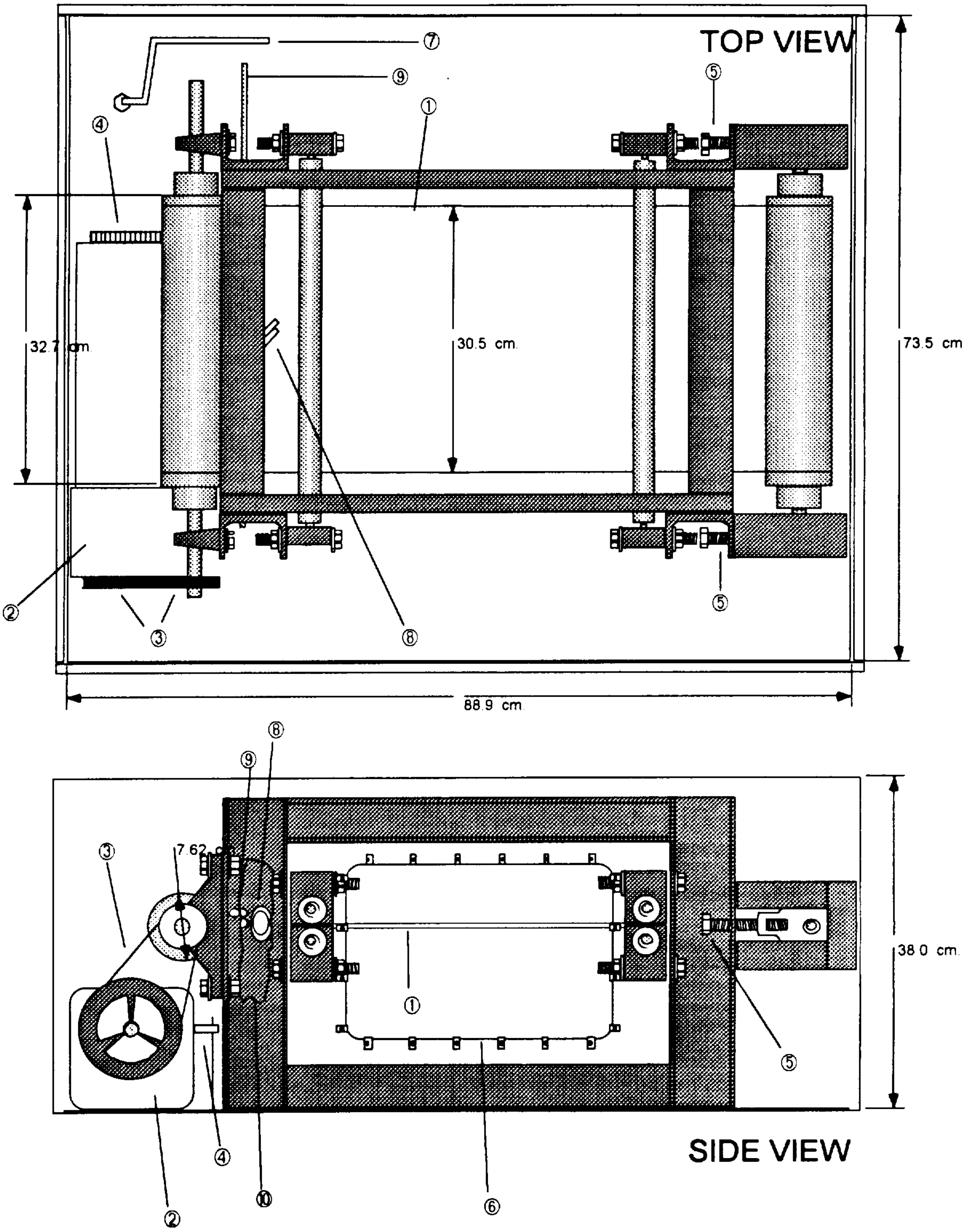


Figure 1 - Current setup of the experimental device.
① Mylar belt ② Motor ③ Pulleys and belt ④ Proximity sensor setup ⑤ Tension adjusting screws
⑥ Glass windows ⑦ Seder ⑧ Mirror for PLIF ⑨ Mirror holder ⑩ Cut through for laser entrance

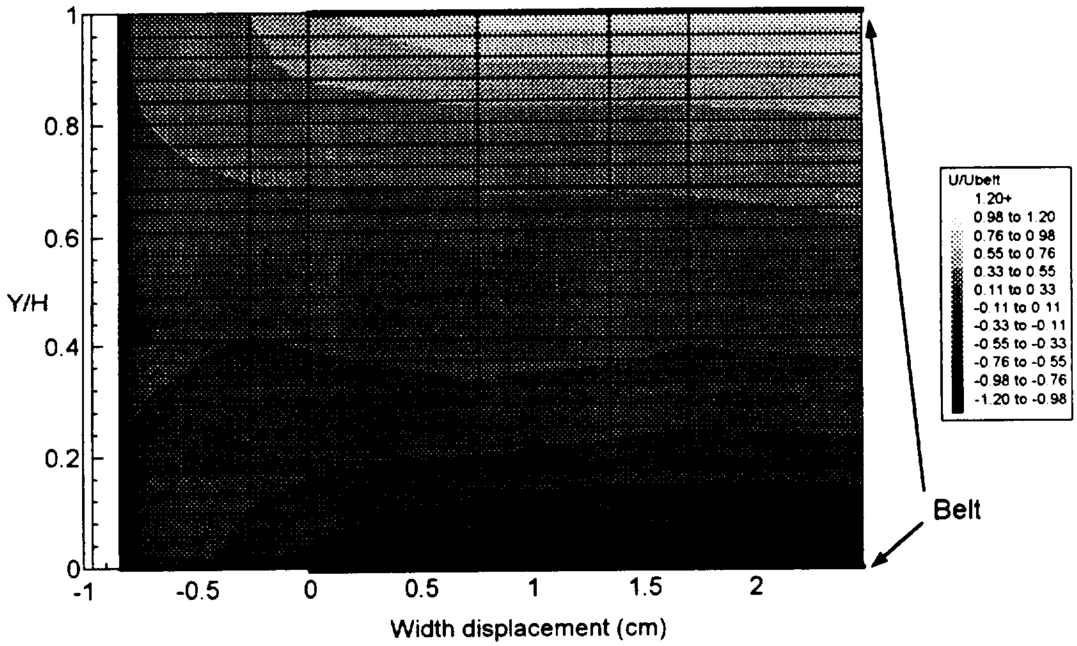


Figure 2 - Special probing of the experimental device shows that the flow is two-dimensional up to about 1cm to 2 cm from the belt edge.

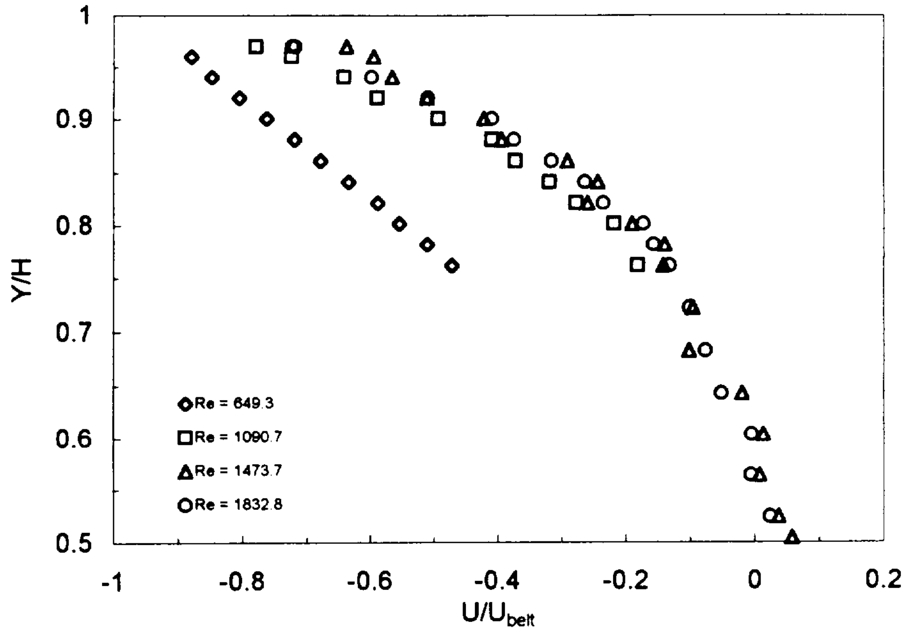


Figure 3a -Turbulent and laminar mean velocity profiles measured in the experimental facility. To very the Reynolds Number U$_{belt}$ and temperature varied; H = 1 cm for all cases.

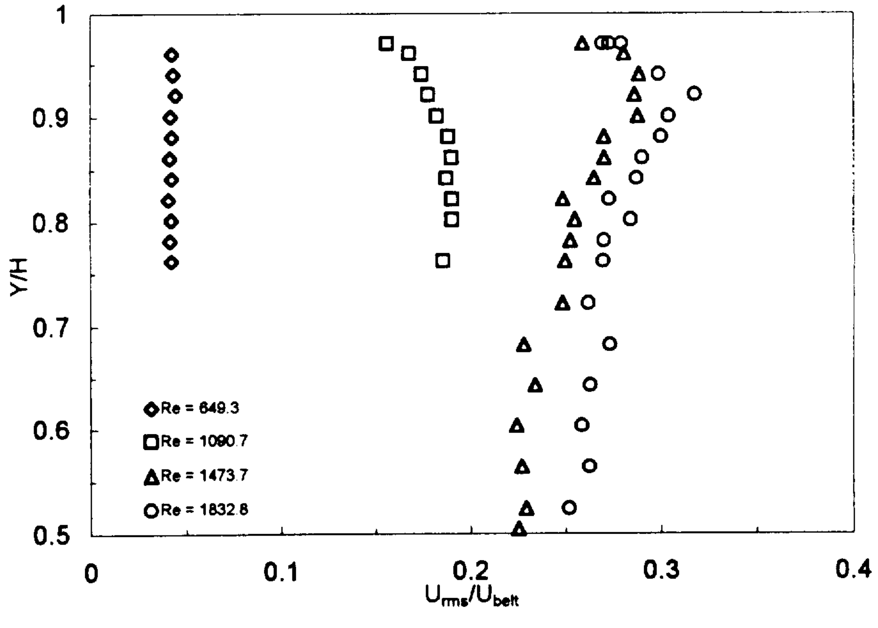


Figure 3b -Turbulent and laminar root mean square velocity profiles measured in the experimental facility. To very the Reynolds Number U$_{belt}$ and temperature varied; H = 1 cm for all cases.

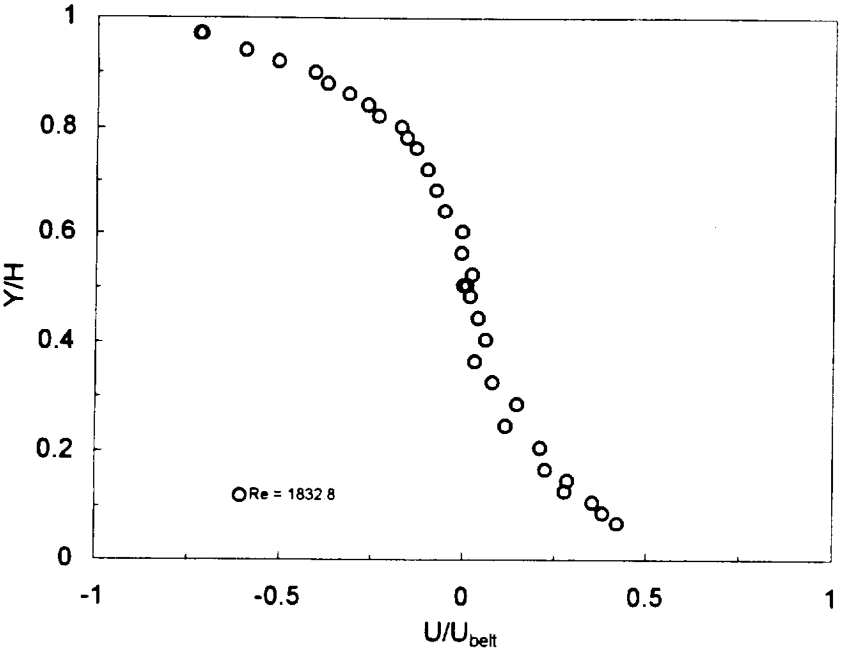


Figure 4a -Turbulent mean velocity profiles measured in the experimental facility. Reynolds Number = 1832.8 was achieved with H = 1 cm and U_{belt} = 3.1 m/sec.

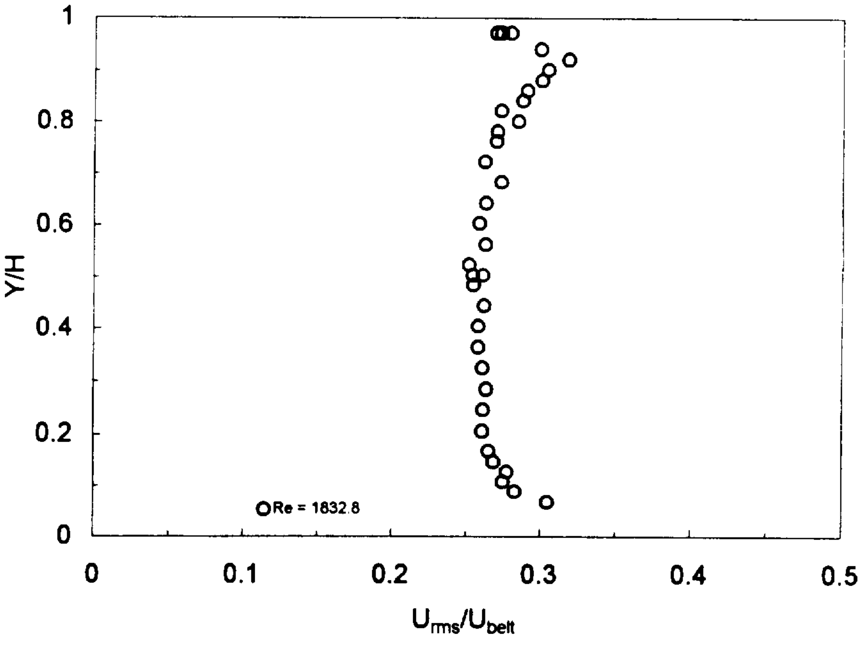


Figure 4b -Turbulent root mean square velocity profiles measured in the experimental facility. Reynolds Number = 1832.8 was achieved with H = 1 cm and U_{belt} = 3.1 m/sec.

Fig 5a. Mean velocity profile in Couette flow
Re = 5200

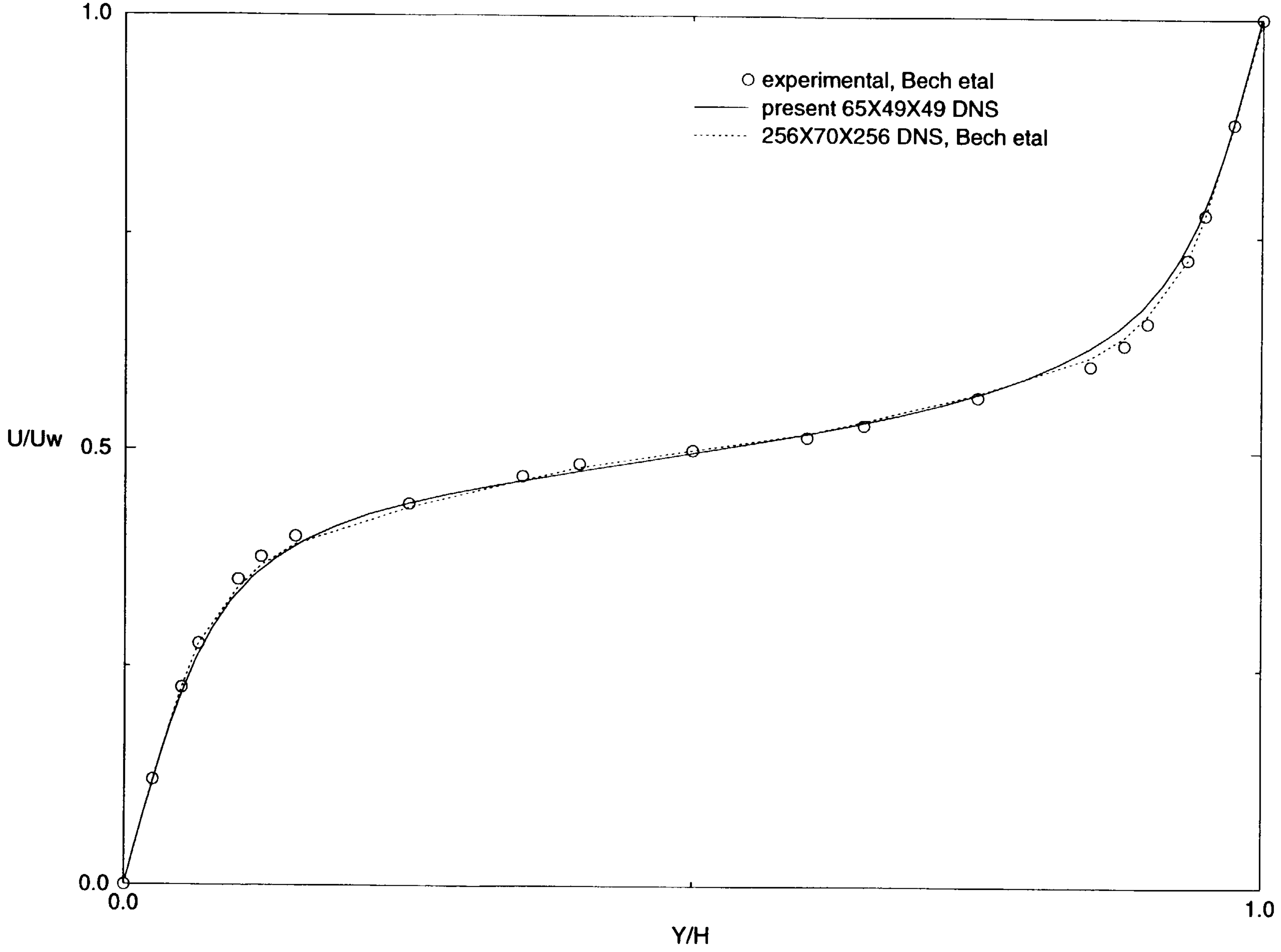


Fig 5b. One point statistics in Couette flow (RMS values of fluctuating velocities)
All RMS values non-dimensionalized using u* , all data collected at around Re of 5200

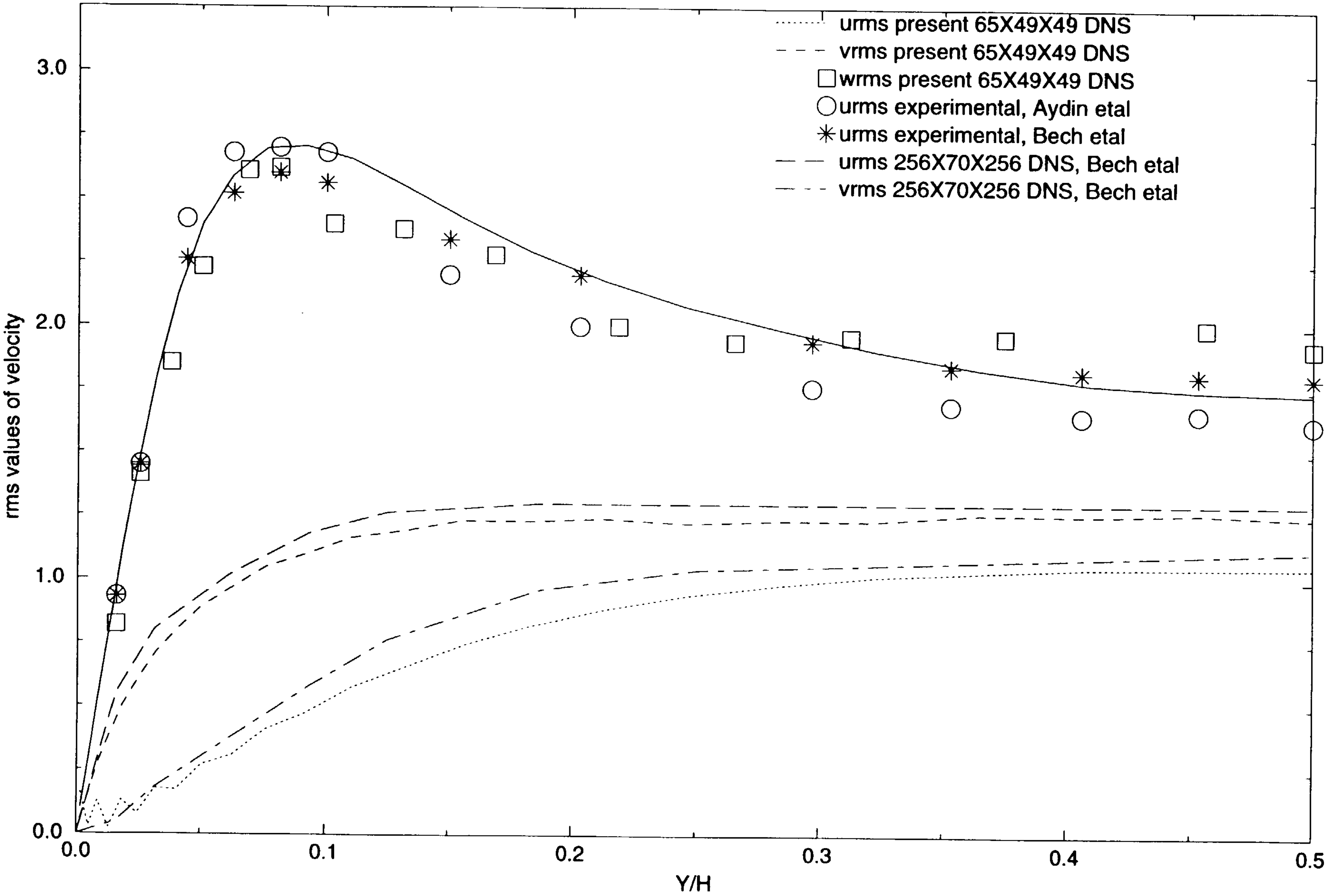


Fig 5c. Comparison of DNS and LES mean velocity profiles

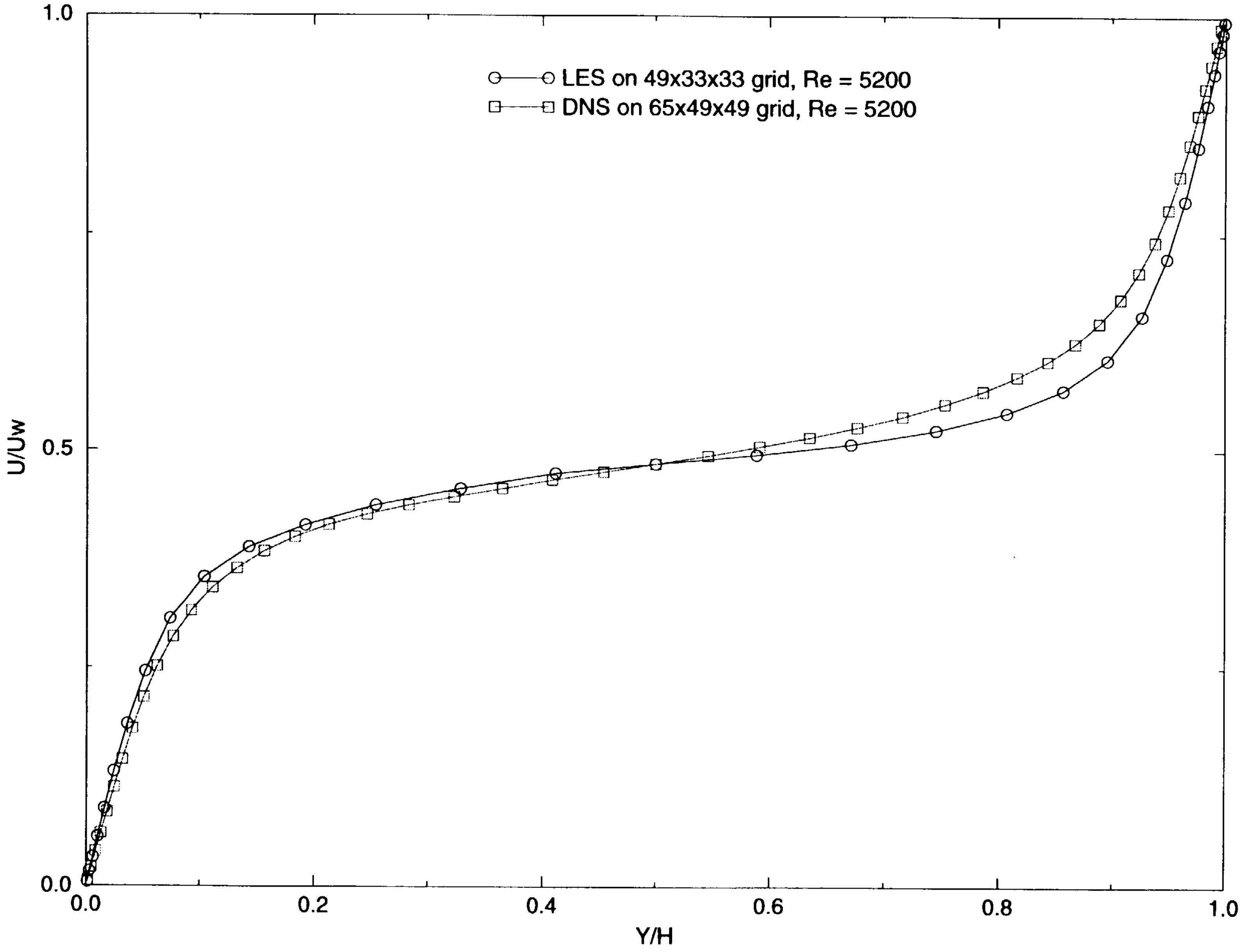
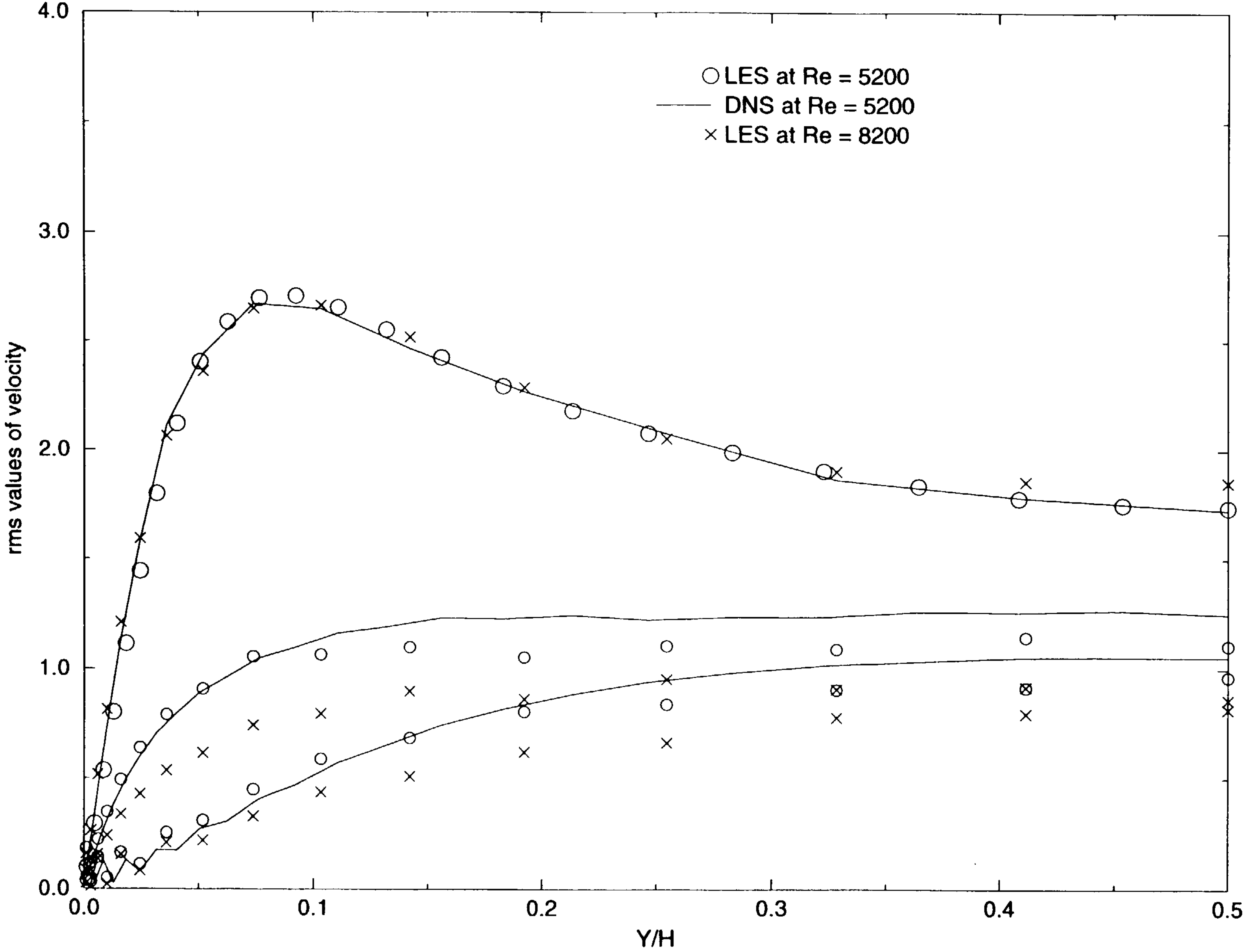
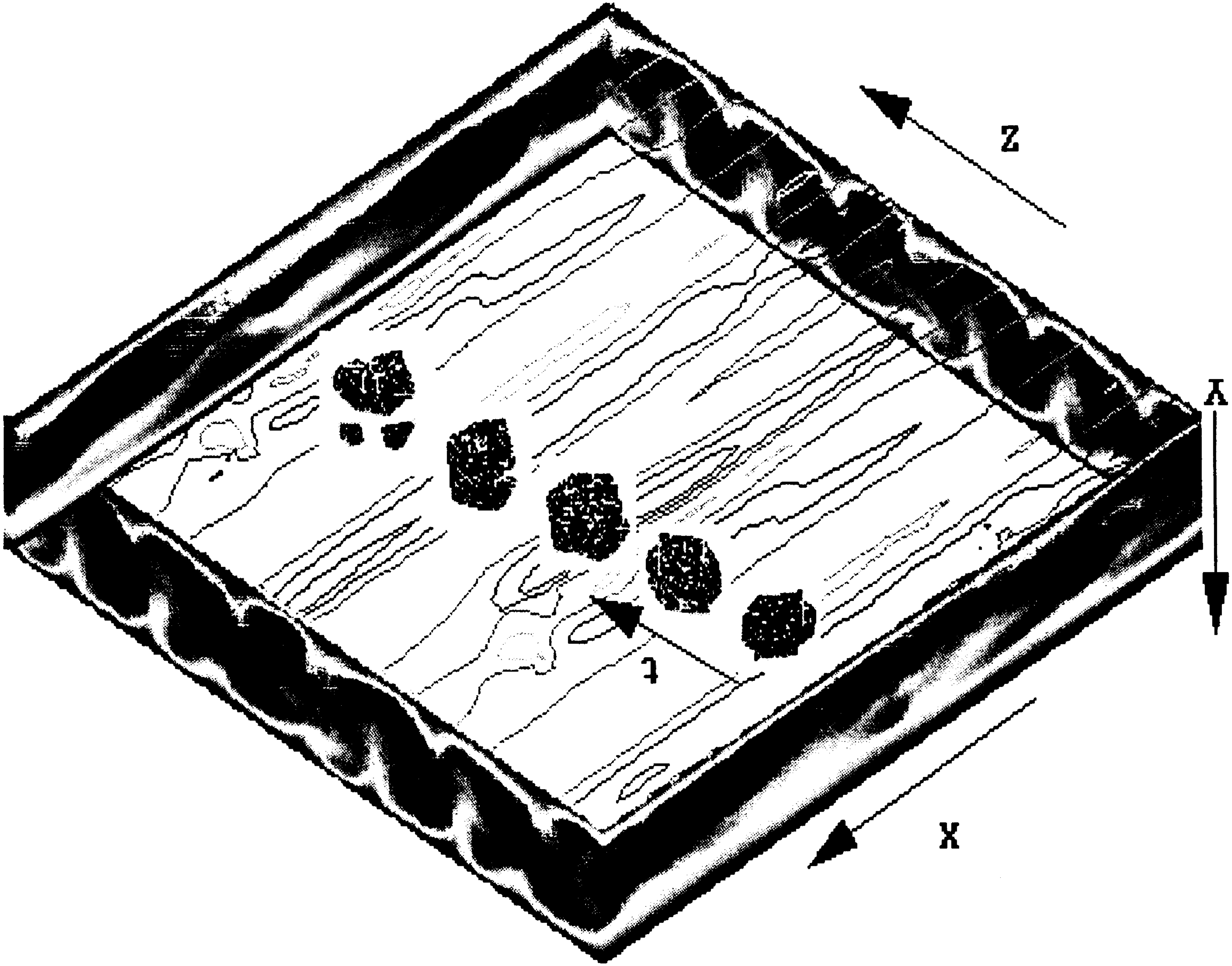


Fig 5d. RMS values of velocities in Couette flow
All RMS values non-dimensionalized using u*

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PARALLEL SIMULATIONS OF UNSTEADY TURBULENT FLAMES

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