Flux Enhancement By Shear Free Surfaces In A Turbulent Convection

Snigdha Lal, Seema Mahto, V. N. Bartaria

Abstract: In this Paper we will be dealing with turbulent natural convection in a long vertical pipe in which the flow is generated because of an unstable density difference across the two ends of the pipe. We create the density difference across the pipe using fresh water and brine. Since the density of brine is greater than that of fresh water, it tries to settle down while the fresh water tries to fill up the upper space. This creates collision of fluid masses in the pipe, leading to a turbulent flow at high levels of density differences. We will study the flow and its effect in the mid section of the pipe. Since water is an incompressible fluid, because of the density difference, the mass of fluid that goes up is equal to the mass of the fluid going down. Thus at any instant of time, the net flow will be zero at any cross section of the pipe. Since the length to diameter ratio (*L/d* ratio) of the pipe is around 9 to 10, the flow will be axially homogeneous. Thus we have an axially homogenous flow with zero mean velocity and which is purely buoyancy driven. This is the basic flow for our experiments.

Index Terms: Axially homogeneous flow, Buoyancy driven flow, Drag reduction, Flux enhancement, Kinematic wall blocking, Shear free surfaces, Turbulent convection.

1 INTRODUCTION

Turbulent flows are ubiquitous. Vastly increased transport compared to molecular effect within them is a main characteristic of turbulent flows. This leads to a few undesirable effects such as an increased skin friction drag. Consequently, drag reduction studies are an important focus of turbulent research. Both active (intervening in a turbulent flow based on a trigger event) and passive (modification of boundaries such as use of compliant surfaces or riblets; or use of additives) techniques abound. See [1] for a review of the drag reduction techniques by the use of additives. [2], [3] and [4] investigated a novel drag reduction technique, based on the attenuation of lateral transport in turbulent flows. Reducing the lateral transport of momentum reduces the drag. Kinematic wall blocking in the presence of solid surfaces can cause the attenuation of lateral transport. To avoid the increase in the drag due to shear boundary layers, the surfaces had to be introduced as a shear free. [2], [3] & [4] demonstrated that drag reduction was possible by this approach. Momentum is not the only quantity transported in a turbulent flow. Many other passive or active scalars are also transported at much greater rates when compared to molecular effects. In this thesis, we study the effect of kinematic wall blocking on the transport of salt in a buoyancy driven turbulent flow. The basic flow chosen is a purely buoyancy driven turbulent flow in a vertical pipe [5]. The flow is generated due to unstable density difference across the ends of a vertical pipe. The flow is having zero mean flow, and is random, and hence the mean shear is zero. The turbulence production due to shear $\langle u_i u_j \rangle \partial U_i/\partial x_j$ is [1]zero, and the buoyancy production $-g_i \langle u_i c \rangle$ is the only source of turbulent energy.

An important consequence for our purpose of zero mean flow here is that as long as the random nature of the flow is not altered, any surface placed within the pipe is a shear free surface (SFS), and thus it should be possible to attenuate the lateral transport. Attenuation of lateral transport would reduce mixing and enhance the axial flux of salt. Thus the effect of placing SFS's into the pipe should be to enhance the axial flux of salt. This paper is concerned with the effect of SFS's in flux of salt along a vertical pipe containing a shear free pure buoyancy driven convection.

Shear Free Surfaces:

Any solid surface introduced into the flow would have a kinematic wall blocking effect. However, a solid surface, in the presence of a flow would also introduce at least one boundary layer where shear is large. This enhances the lateral transport of momentum, more than counteracting the attenuation brought about by the kinematic wall blocking effect. Hence it is necessary to introduce these surfaces without shear, to derive any benefit from the kinematic wall blocking effect. In the experiments done earlier, we used thin plastic strips as shear free surfaces in a horizontal pipe. These strips caused a kinematic wall blocking effect which in turn reduced the lateral transport of momentum, and hence the drag in the pipe. Shear free surfaces attenuate the normal velocity fluctuations, hence attenuating the transport of momentum in that direction and thus modifying the local velocity profile. This is confirmed by the fact that the low density polythene strip (20µm grade) is moving faster than the local average velocity. This has a global effect because of continuity, even far from the regions of direct influence of the shear free surfaces, the slope of the velocity profile reduces and the drag reduces. The timescale of this phenomenon is the slow turbulent timescale, although the kinematic blocking itself is expected to occur in the rapid timescale. This is confirmed by the speeds of strips of different lengths. In the present experiments, the shear free surfaces are in the form of long steel rods. We expect the overall flux to increase as we increase the diameter of the rod. These rods are placed at the centre of the pipe i.e., they coincide with the axis of the pipe.

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2 EXPERIMENTAL SETUP

The experimental setup consists of an arrangement of two tanks, of 20cmX20cmX15cm volume, made of Perspex and glass, and connected to each other with the help of a pipe of circular cross section (50mm diameter). The tank which is kept below is closed from all sides, and is open only at the junction which connects it to the above tank through the pipe. There are no other openings connecting the two tanks. The tank openings are sealed by rubber stoppers with the help of a jack which is placed below the lower tank. The schematic of the setup is shown below:

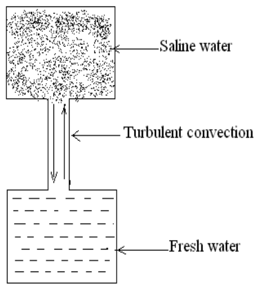

Fig. 1. Schematic of experimental setup

At the start of the experiment, fresh water is put in the lower tank and the pipe, while the upper tank is filled with saline water. The two fluids are separated from each other with a stopper. The experiment is initiated by removing the stopper. After the initiation of the experiment, the fluids start mixing with each other because of the flow in the pipe. Because of density difference the saline water will try to move to the lower tank. Since water is incompressible, the salt water flowing to the lower tank will displace an equal volume of fresh water from the lower tank. These interact and mix within the pipe, generating turbulence. A net transport of salt takes place from the upper to the lower tank. Because there is no net flow within the pipe, the mean flow and hence the mean shear within the pipe is zero. Eventually, the density difference across the pipe reduces and the flow first becomes laminar and then finally stops. We are interested in the turbulent part of the flow. Fig. 2 is the photograph of the actual setup. Two aquarium pumps are connected separately to the upper and the lower tanks. These pump the water from the bottom of each tank to provide uniform boundary conditions to the pipe by avoiding stratification of fluid in each tank. The flow rate is low enough not to disturb the flow at the pipe exit.

Fig. 2. Experimental setup

3 EXPERIMENTS

The experiments were done in the setup explained earlier. Turbulent convection was produced in the long vertical pipe and the flux of salt in the pipe was measured. We start by first measuring the volume of the setup just below the upper tank, i.e. volume of the lower tank and the pipe. Then fresh water was filled in the tank to the double of the volume measured before. The pumps connected to the upper and lower tanks were always in running conditions ensuring uniformly mixed conditions in the tanks and thus avoiding stratification. We take the readings of concentration of this plain water using the conductivity probe (*ORION 3 STAR BENCHTOP, MODEL 013005MD*). 0.1% salt by weight of the volume of water in lower tank was used to mix in the upper tank. The upper and lower tanks were separated using a stopper. After adding the salt in upper tank, the concentration of this solution was measured. The experiment is then started by removing the stopper. These experiments lasted for about 3 hours and eventually the turbulent flow in the middle section of the pipe decays. The pumps are running throughout the experiment. Once the experiment is over, all of the fluid in the setup is collected in another tank and mixed thoroughly. The concentration of this solution is then measured. This completes one full experiment, in the absence of any inserts, to measure the base condition of the flux. A large set of readings have been taken so as to compare these and study the effects of changing the experimental conditions of the experiment. The experiments are done with shear free surfaces. Since the flow is with zero mean, any stationary surface in the flow is a shear free surface, as long as the flow remains random. We have used cylindrical rods as inserts along the pipe axis as shear free surfaces. Rods of 2mm, 5mm and 10mm are used as inserts. The insert is placed within a few seconds of the removal of the stopper. Finally a small number of experiments are done to test the effect of the end conditions by increasing the stratification. This is done by either reducing the mixing using pinch cocks to reduce the flow rates of the pumps or by switching the pumps off altogether. The above details are given in the following table:

Table1. Details of experiments:

Sl. No.	Condition	Number of Experiments
1.	No Inserts	10
2.	2 mm Insert	10
3.	5 mm Insert	10
4.	10 mm Insert	13
5.	With Pinch Cocks	03
6.	With Pumps Off	02

We compare the results of these experiments by processing the data obtained by all the above experiments.

Measurement of dissolved salt:
Initial trials with the conductivity probe showed that the measurement of dissolved salt using the meter was unreliable. Hence we decided to just measure the conductivity of the solution using the meter and hence calculate the amount of dissolved salt allowing for temperature effects, using conductivity data for aqueous solution of salt. This procedure has proved satisfactory. For this purpose we use conductivity data of aqueous salt solutions. Since this data is at 20^0 C, while the results are reported typically at 25^0 C. Hence a correction is made as:

$$\text{Conductivity}_{25} = \text{Conductivity}_{20}/\{1 + \alpha(20 - 25)\}$$

This conductivity of the solution and the temperature of the solution are measured and acquired automatically via an *RS232* interface every 5 seconds and written into a file. The conductivity value is corrected to the deviation from 25^0 C and then a look up function constructed from standard tables [6] is used to determine the dissolved salt concentration in ppm. We calibrated the instrument for this procedure by dissolving known amounts of salt in a liter of water and measuring it. Both tap water and deionized water were used. Salt was weighed in a balance of least count 10 µg. Salt was added from 1g – 15g in steps of 1g, in a litre of water. The least count of water volume measurement was about 20 cc. The conductivity was then measured using the probe, and the measured value of the dissolved salt was compared. Before each calibration the probe was calibrated for its cell constant using a standard solution provided. The nominal value of expansion coefficient is a little low and the calibration results in a value of $\alpha = 2.25/^0 C$. Typically the maximum error is ± 200 ppm (less than ± 2%).

Measurement of flux:
By knowing the rate of variation of concentration of salt with respect to time in the top tank, we can determine the concentration difference 'ΔC' and the flux of salt concentration 'F' using an integral balance of mass of the salt within the pipe as follows:

$$C_B(t) = [M_S - C_T(t)(V_T + V_P/2)]$$

The relation of concentration to density are given by:

$$\frac{d\rho}{dC} = \rho_0\,\beta$$

$$\Delta\rho = \rho_0\,\beta\Delta C$$

$$\rho = \rho_0 + \Delta\rho = \rho_0 + \rho_0\,\beta\Delta C$$

Where,

ρ_0 : Density of water;

β : 0.72 for salt concentration range in the experiment;

$\Delta\rho$: Density difference between top and bottom tank fluids.

Data reduction:
The conductivity data is first processed before fluxes are evaluated. Since the calculation of flux involves the time derivative of conductivity the raw data results in an extremely noisy evaluation of the flux. Here we describe the steps involved in and the choice of the data processing procedures. The flux calculated from the raw data is extremely noisy. The normalized flux is plotted hence it should be close to 1. A simple moving average over 25 seconds (5 point average) before the flux is calculated greatly reduces the noise, but still is very noisy. A simple Fourier mode truncation and an inverse transform after the flux is calculated, reduces the noise further. A 5 point moving average on flux followed by a truncation to 20 Fourier modes reduces the noise to about 60%, if we reduce the Fourier modes to 2, the noise is about 20%. However this approach assumes the normalized flux to be a constant, which is unknown *aprior* in the case where the SFS's are introduced. Hence the approach was to fit an exponential polynomial in the form of $e^{\sum_n a_n t^n}$ to the raw data before the flux is evaluated. The approach has proved to be quite satisfactory. Figure 10 shows the result for a 6^{th} order fit for conductivity followed by the calculation of the flux. The normalized flux is constant and is at about 1. For a few sets of data experiments, beyond the 5^{th} order, the data becomes ill conditioned and the fitting becomes poor. 5^{th} order polynomial fitting is chosen.

4 RESULTS AND DISCUSSIONS

Table 2 gives the representative values for the ratio F/F_T.

Table 2: Normalized flux and relative blockages for various inserts

Sl. No.	d_i/d	Relative blockage $(d_i/d)^2$%	F/F_T, Normalized flux %
1	2/50	0.16	10
2	5/50	1	12
3	10/50	4	15

It can be seen from the table that scaling F/F_T works well for the cases with inserts also, over a range of *Ra*. This is indicative that mixing length velocity and length scaling are still valid, and also the nature of the flow is similar to the open pipe case. Also as expected, the flux has increased. Even for an insert of 2mm, the flux has increased by about 10%. This is disproportionate to the area of blockage; a 2mm rod in a pipe of 50mm constitutes a blockage of (1/625) = 0.16%. However the flux has increased by 10%. This trend continues to larger blockage ratios of the 5mm and 10mm rods, increasing to 12% and 15% (blockage ratios of 1% and 4% respectively). Figure 3 shows these trends (the last point of 20mm rod is from [7]). The figure also shows how the flux would be reduced if there is no enhancement, due to the blockage effect of the rods.

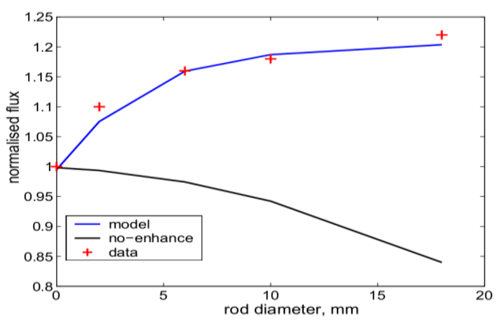

Fig. 3 Variation of flux enhancement with size of the insert

These results confirm the hypothesis that the flux is indeed affected positively by the kinematic wall blocking effect of the SFS's; the kinematic wall blocking attenuates the lateral mass transport, thus enhancing the axial transport, and thus increasing the flux. PIV measurements done by [8] show that the velocity correlation maps have become elongated due to the presence of the shear free surfaces, indicating increased regions of coherence. This is due to the reduced decorrelation due to the decreased lateral transport mechanisms. Figure 4 shows the velocity auto correlation maps for the flow with no inserts ([5], [7]).

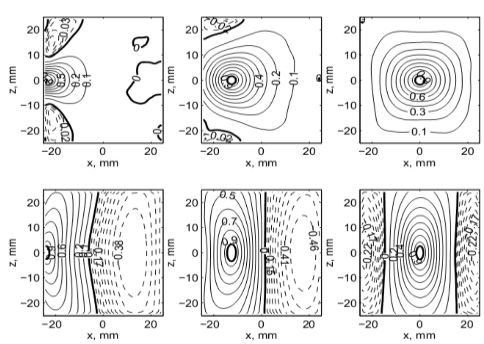

Fig.4 Velocity auto correlation maps with no inserts, lateral velocity (top); axial velocity (bottom)

It can be seen from figures 4 & 5 that the region of coherence in the vertical velocity has become elongated in the presence of the SFS while the lateral velocity correlation map is not much affected.

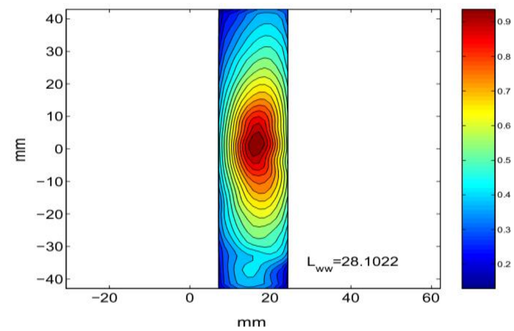

Fig. 5 Velocity auto correlation map for a 10 mm insert, axial velocity

The kinematic blocking typically extends on an integral length (in terms of the wall normal velocity fluctuations) into the flow. We model the flow to consist of three distinct layers; a viscous zone next to the SFS, the region with kinematic wall blocking next to it, where flux enhancement takes place, and an outer zone affected by the presence of SFS (See figure 6). We model the flux enhancement to decrease linearly from F_e/F_0 to 1 in layer 2. Also we stipulate that this layer is either the transverse length scale of the flow or proportional to the diameter of SFS, say *md* whichever is smaller. This is relevant to smaller diameter SFS's, where the effect of the SFS is limited by its curvature.

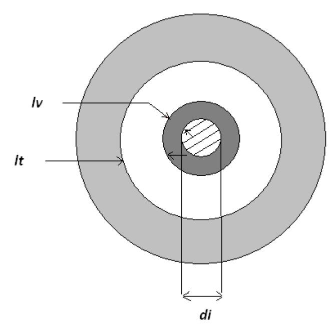

Fig.6 Schematic showing the regions assumed in the model

Figure 3 shows the results of this model with F_e/F_0 = 2.55, m=2 and l_v= 1mm. l_v is obtained as a viscous diffusion length scale with an integral timescale of about 1s. The measured flux ratios are well captured.

5 Conclusion

To summarize, these results show the evidence of flux enhancement due to the presence of SFS's. These affect the large scales of the flow, and through kinematic wall blocking, attenuate the lateral transport and hence enhance the axial transport of flux. Measurements show an increase of up to 20% in flux for a blockage ratio of 16%. Smaller blockage ratios have a surprisingly larger relative enhancement. A simple model describing the flux enhanced flow to occur in three distinct regions captures the trend reasonably well.

Effect of different geometries for SFS's, can be investigated similarly. PIV can be performed to determine the velocity statistics and clarify some aspects of the transport processes altered by the presence of the SFS.

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REFERENCES

[1]. Lumley, J. L. Drag reduction by additives, Ann. Rev. Fluid Mech. 1 pp. 367-384, 1969.

[2]. Kathuria, A. and Shukla, G. Experimental investigation of drag reduction by macro additives in a turbulent pipe flow, SURA report, IIT Delhi, 2008

[3]. Raja Vamsi, G.,2009 Drag reduction by modifying the large scales of a Turbulent Channel flow, Master of Technology Thesis, Department of Applied Mechanics, IIT-Delhi.

[4]. Tarak Kumar Sahoo, 2010 Drag reduction by modifying large scales of a Turbulent flow, Master of Technology Thesis, Department of Applied Mechanics, IIT-Delhi.

[5]. Cholemari, M. R. Flux enhancement by modifying the large scales of a turbulent flow, Unpublished.

[6]. CRC Handbook of Physics and Chemistry, 82nd Edition, Lide, D. R., Ed.,CRC press, 2001.

[7]. Cholemari, M.R. and Arakeri, J.H. Experiments and a model of turbulent exchange flow in a vertical pipe, Int. J. Heat Mass Trans., 48, pp. 4467-4473, 2005.

[8]. Cholemari, M.R. and Arakeri, J.H. Axially homogeneous, zero mean flow buoyancy-driven turbulence in a vertical pipe, J. Fluid Mech., 621, pp 69-102, 2009.