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AN EXPERIMENTAL AND NUMERICAL STUDY OF DEVELOPED SINGLE
PHASE AXIAL TURBULENT FLOW IN A SMOOTH ROD BUNDLE

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SUMMARY

A combined experimental and numerical model of a turbulent single phase coolant, flowing axially along the fuel pins of a nuclear reactor, was developed. The experimental rig represented two interconnected subchannels of a square array at a pitch/diameter ratio of 1.193. Air was the working fluid, and measurements were made of the mean radial velocity profiles, wall shear stress variation, turbulence velocity spectra and intensities. The numerically predicted wall shear distribution and mean velocity profiles, obtained using an empirical two-dimensional mixing length and eddy diffusivity concept to represent fluid turbulence, showed good agreement with the experimental results.

1. INTRODUCTION

The problem of predicting the momentum losses and convective heat transfer performance of clustered heat generating rods, cooled by an axially flowing fluid, is of significant interest to the nuclear power industry. A series of design techniques has been developed to predict the thermal and hydraulic performance of reactor fuel elements. Present techniques use mainly lumped parameter methods which are capable of predicting only the average flow and enthalpy within the flow subchannels. For large bundles of fuel rods, typical subchannels may be reduced to the three- and four-rod array (Figure 1). However, with the advent of the fast reactor with its more closely spaced rods (lower p/d ratio) and greatly increased rod surface heat flux, the local anisotropy of the heat removal process by the turbulent coolant may introduce significant temperature differences around the fuel rod. A more detailed and finer scaled technique of thermal and hydraulic analysis is thus desirable.

Historically, a hierarchy of calculation methods have been applied to this problem, in which the level of approximation to the Navier Stokes momentum and energy equation is related to the amount of empirical input required for solution. This hierarchy has been reduced (Lewis & Buettiker 1974) to four main divisions: the channel averaged (or slug flow) approximation, integral methods based on the law of the wall, eddy diffusivity models and turbulence kinetic energy models. The channel averaged method performs simply a heat and momentum balance for the whole rod cluster and assumes a flat velocity and temperature profile at each axial position along the channel. Extensive experimental work on individual fuel bundle designs is required before empirical correlations can be developed for the momentum loss and heat transfer, which are required as the input data; such correlations have very limited extrapolation properties.

A modification of this technique, developed to provide more detailed information on individual fuel elements, divides the rod bundle into flow subchannels (Figure 1). Such subchannels are arbitrarily defined and do not necessarily form areas of flow symmetry. Each subchannel is then regarded as a separate flow area with a friction factor and surface heat transfer coefficient derived from experimental data for flow in simple geometries (e.g. pipe, annulus). The fluid interface between each subchannel is considered to provide a means of heat, momentum and mass transfer between adjacent subchannels. However, the coefficients used for this transfer must be determined by an experimental program, specific to each bundle geometry.

Integral methods of predicting the velocity and temperature profiles are related to the law of the wall. Where the local rod wall shear stress can be obtained for developed flow the law of the wall provides an accurate prediction of the mean velocity profile. The temperature prediction, relying on the Reynolds analogy between heat and momentum transfer, is less precise.

The eddy diffusivity concept attempts to model the turbulent stress tensor and heat flux vector by diffusion coefficients related to some property of the local time averaged flow. The reduced Navier Stokes and energy equations are still second order non-linear differential equations which usually require a numerical solution technique. Although the concept of an eddy diffusivity is artificial it represents one further step in the search for generally applicable

functions, measurable in simple geometries and transferable to more complex flow geometries. Variations in local rod wall shear stress within the symmetry zone of a subchannel, can be accurately predicted using the eddy diffusivity concept, together with the radial mean velocity profile as preliminary results of the experimental program demonstrate.

The most general design calculation method, as yet still being developed, uses the local turbulence kinetic energy and a local turbulence length scale to model the fluid transport properties.

The Reynolds stress terms in the Navier Stokes equation are themselves represented by a function of the above variables, in an equation derived as a moment of the Navier Stokes equation. Although this technique requires considerable increase in computing effort, it is the most promising having the most predictive features.

All the above methods normally use a simplified constant material property fluid; the last two may be adapted to a variable property fluid, with considerable increase in complexity and computing time. This is because the already non-linear momentum equation is coupled to the now non-linear energy equation, adding a further outer loop in the iterative solution method. In view of the empirical nature of the coefficients used in these two methods, this degree of complexity is not warranted at present.

2. EDDY DIFFUSIVITY OF MOMENTUM AND HEAT

The numerical solution to the mean flow distribution within either large three-, or four-rod subchannel arrays, used an eddy diffusivity approximation to the fluid turbulence. This eddy diffusivity model was adapted from the three-dimensional mixing length theory of Buleev (1963), to solve the reduced momentum and energy equations (1) and (2) for fully developed flow;

$$\frac{1}{\rho} \frac{\partial \bar{p}}{\partial z} = \frac{\partial}{\partial r} \left[r \left(\epsilon_m^r + \nu \right) \frac{\partial \bar{v}}{\partial r} \right] + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left[\left(\epsilon_m^\theta + \nu \right) \frac{\partial \bar{v}}{\partial \theta} \right] \quad (1)$$

$$\frac{\bar{v}}{k_c} \frac{C_p \rho}{C} \frac{\partial \bar{T}_c}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \left(\epsilon_H^r \frac{Pr}{\nu} + 1 \right) \frac{\partial \bar{T}_c}{\partial r} \right] + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left[\left(\epsilon_H^\theta \frac{Pr}{\nu} + 1 \right) \frac{\partial \bar{T}_c}{\partial \theta} \right] \quad (2)$$

Details of the numerical method of solution adopted have been described (Hooper 1974,1975); a significant feature of the numerical mesh employed was the use of a logarithmic radial mesh spacing in the near wall region. This mesh allowed the location of at least two velocity points within the sublayer flow region ($y^+ \leq 5$); this condition was found to be important for the numerical stability of the finite difference calculation. This fine mesh cannot be extended over the whole flow area, though the requirement for it is probably general to turbulent flow calculations if details of the near wall region are required.

The Buleev model has two important advantages over point velocity gradient expressions for the eddy momentum diffusivity: one, that a general line integral expression, applicable to all the flow regions, is used for the diffusivity at each mesh point. This function does generate zero diffusivity values in the sublayer region. In addition, the radial momentum eddy diffusivity does not become zero at flow locations where the local mean velocity gradient is zero. With a detailed prediction of the momentum transport properties of the fluid in the near wall region, a solution for both the rod and fluid temperatures can be developed if some analogy between heat and momentum diffusivity is assumed. A power series approximation to the temperature distribution in the fuel rod can readily be linked to the fluid coolant, if both the velocity and temperature distributions in the fluid are fully developed (Thompson and Holy, 1975, Hooper 1973). This model shows the critical nature of the near wall region for non-metallic coolants, and the corresponding need for a predictive model which gives details of fluid turbulence in this region.

3. EXPERIMENTAL PROGRAM

Most experimental data reported for heat transfer and flow distribution within rod bundles have been for channel averaged properties, and so, until recently, there was no experimental information available for the development of turbulence models in this geometry. Accordingly an experimental program was planned, in which mean flow quantities (wall shear stress, axial pressure gradients, mean velocity distribution), and turbulence intensities and Reynolds stresses would be measured in a large scale section of two interconnected subchannels. Numerical results showed that the wall shear stress variation for a three-rod subchannel was less than that for a four-rod subchannel at the same (p/d) ratio and Reynolds number, (Figure 2), and as the wall shear stress variation was a parameter of interest the four-rod cluster was adopted. The flow

area thought to be a close approximation of an infinite array of square pitched rods is shown in Figure 3a, and the rig layout in Figure 3b. The (p/d) ratio used was 1.193, as earlier numerical studies had shown that the influence of the subchannel gap wall at this spacing for laminar flow would not extend to the subchannel centre (Hooper 1975). With turbulent flow conditions and neglecting secondary flow effects, the influence of the gap wall was expected to be less. Subsequent experiments are planned at (p/d) ratios of 1.10 and 1.05 which will further reduce this effect.

The rod diameter was 14.0 cm, with a total test section length of 9.14 m. Air was the working fluid, and the total air flow from the 45 kW two-stage centrifugal blower was measured by orifice plate before entry to the settling tank (Figure 3b). The axial pressure gradient was measured by 18 equally spaced static pressure tapping points; a least squares approximation was used to fit the measured static pressures for the linear region. Measurements of the mean flow, wall shear stress, turbulence intensities and spectra were made at the end of the test section, at a length/hydraulic diameter ratio of 95. The wall shear stress was measured by a Preston tube, using the correlations of Patel (1965).

The turbulent velocity components were measured by a constant temperature hot-wire anemometer, using a circuit developed by the I.S.V.R. Southampton University, U.K., and marketed commercially. The single straight wire and single inclined wire probes used a 5 μ m diameter tungsten wire, with an active length of 2 mm. The probe response laws used were developed by Davies and Davis (1966), Davies and Bruun (1969) and Bruun (1976), for the same probe wire dimensions.

All data were entered directly into a PDP11 computer with associated disc storage, with the spectra of the turbulence signals generated by a Spectral Dynamics Corporation model SD301B analyser attached to this computer (Harris 1973).

4. EXPERIMENTAL RESULTS

4.1 Wall Shear Stress Variation

The variation of the wall shear stress about both central rods of the rig is shown in Figure 4, together with the predicted shear stress variation for an equivalent large array Reynolds number of 1.29×10^5 . The experimental points show good symmetry for both top and bottom rods, and also indicate symmetrical flow in the interconnected subchannels. The effect of the rod gap wall is also present to within 25° of this wall. The predicted shear stress variation shows good agreement with the experimental points in the interconnected rod gap region ($\theta = 0$) though the maximum point in the experimental shear stress occurs nearer the rod gap area. This flattening of the shear stress variation is thought to be due to the influence of secondary flows (Carajilescov & Todreas 1975, Trupp & Azer 1974, Kjellström 1974).

4.2 Mean Velocity Profiles

The experimental radial mean velocity profiles from the rod gap ($\theta = 0^\circ$) to the subchannel centres ($\theta = 45^\circ$) are shown in Figure 5. The near wall region was measured by a boundary layer probe, with the rest of the profile determined by a Pitot probe. For the subchannel centreline profile ($\theta = 45^\circ$), the results for measurements in both interconnected subchannels are shown, and the agreement between the curves shows good symmetry between the interconnected subchannels. The numerical prediction which is included is also in agreement for the subchannel centreline plot ($\theta = 45^\circ$). The displacement in the boundary layer profile in the near wall region is thought to be due to a systematic measurement error.

4.3 Turbulence Intensities and Spectra

The intensity of the axial turbulent velocity component is shown in Figure 6 together with measurements of the Reynolds stress. These results are in general agreement with reported data for flow in three-rod clusters (Kjellström 1974) though at present there appear to be no reported turbulence data for flow in four-rod subchannels. The spectra of the turbulent velocity components which are shown in Figure 7, are also similar to the results for three-rod clusters (Trupp & Azer 1974, Kjellström 1974).

5. CONCLUSIONS

The experimental wall shear stress showed good symmetry, and agreement with the numerical prediction for the region away from the rod gap wall. The flattening effect of secondary flows on the wall shear stress was slight, though the reduction of the wall shear to the mean value in the subchannel centre as reported by Carajilescov & Todreas (1975) for a three-rod cluster was not present.

The numerical mixing length model generated mean velocity profiles which were in good agreement with the experimental mean velocity measurements, particularly in the subchannel centre ($\theta = 45^\circ$).

Further detailed turbulence measurements to be made should enable a turbulence kinetic energy model to be applied to the numerical prediction of flows in this geometry.

6. ACKNOWLEDGEMENT

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8. NOTATION

		k_1	One dimensional wavenumber
(p/d)	Pitch to diameter ratio	k_c	Fluid thermal conductivity
y^+	Dimensionless wall distance	C_p	Fluid specific heat
$\bar{v}$	Mean flow velocity	p	Static pressure
v^*	Friction velocity	u, v, w	Turbulent velocity components
τ_w	Wall shear stress	Subscripts m	Momentum diffusivity
$\bar{T}_c$	Mean flow temperature	H	Heat diffusivity
ρ	Fluid density	Superscripts θ	Tangential component
ν	Fluid kinematic viscosity	r	Radial component
Pr	Fluid Prandtl number	$\wedge$	Maximum value
ϵ	Eddy diffusivity		
y	Wall distance		

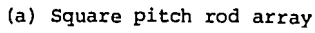


Figure 1

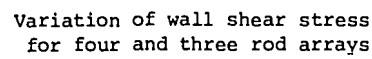


Figure 3(a)



Figure 3(b)

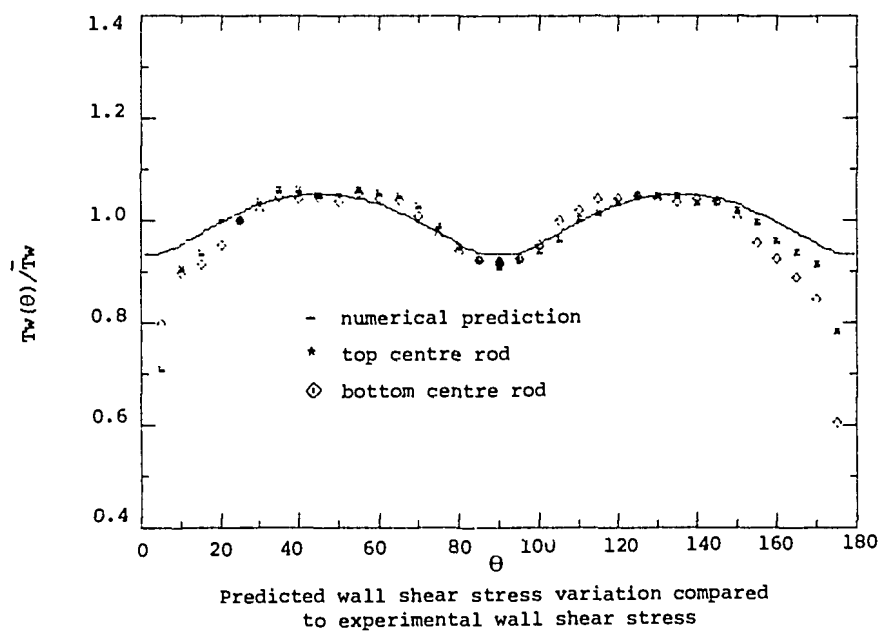
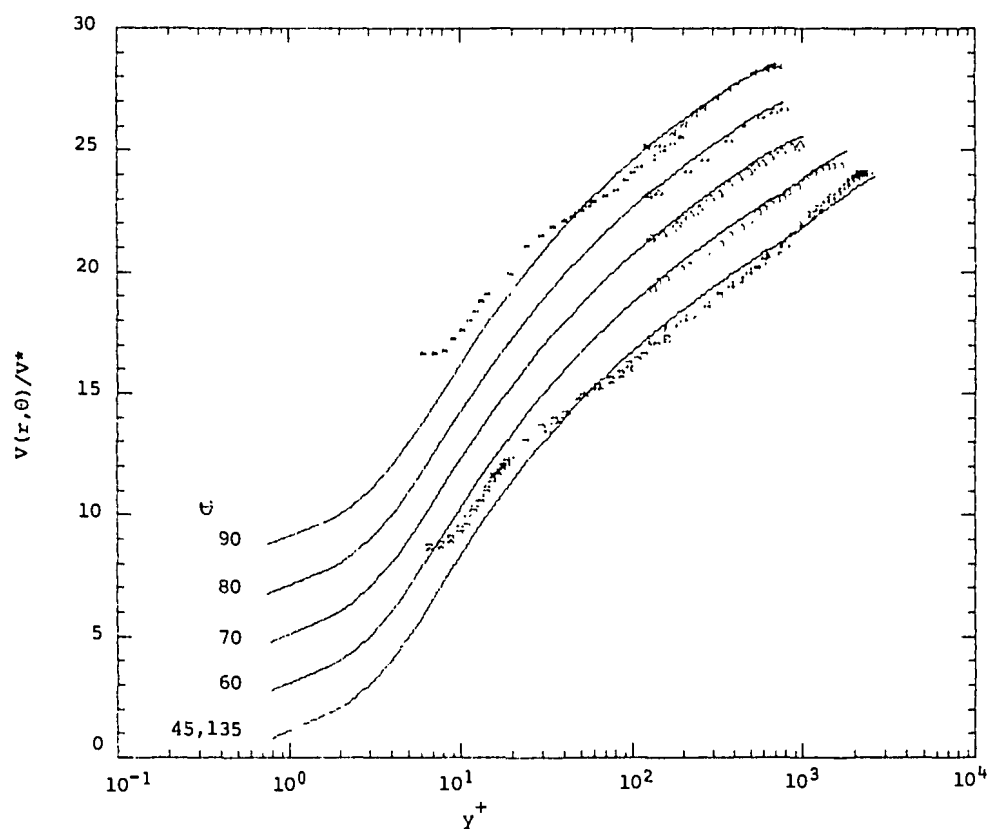


Figure 4



Predicted $V(r, \theta)$ mean velocity compared to experimental velocity distribution. A constant of 2.0 has been used to displace successive curves from the $\theta=45$ and 135 distribution

Figure 5

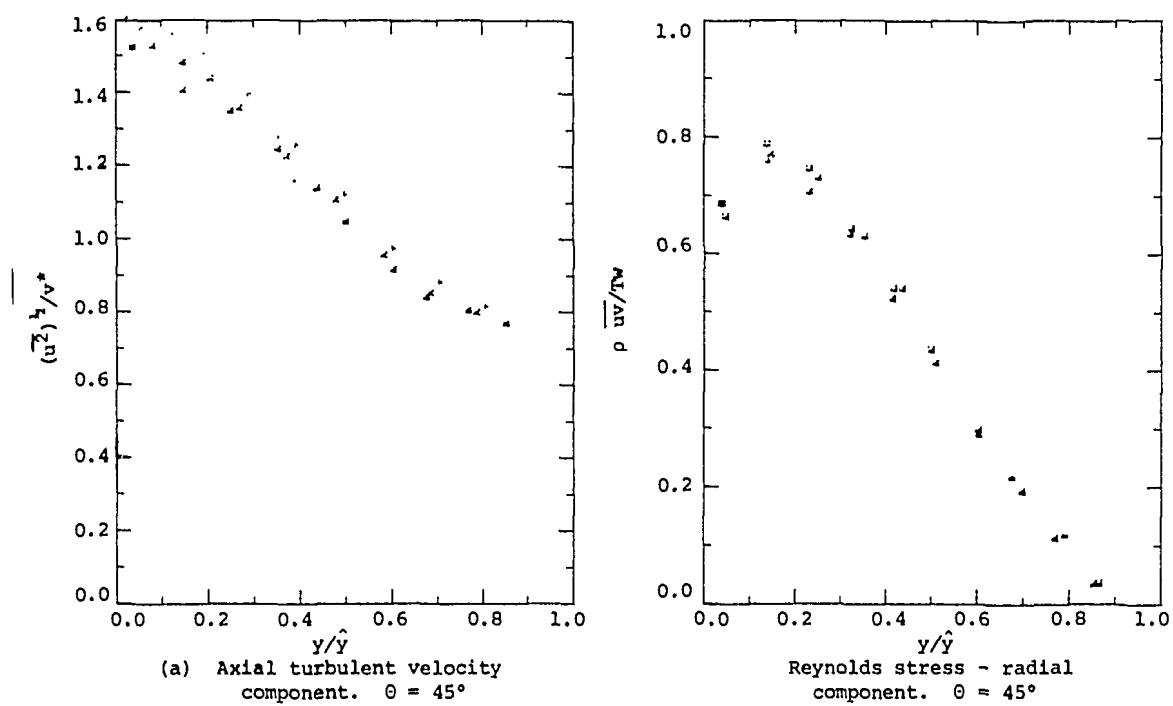
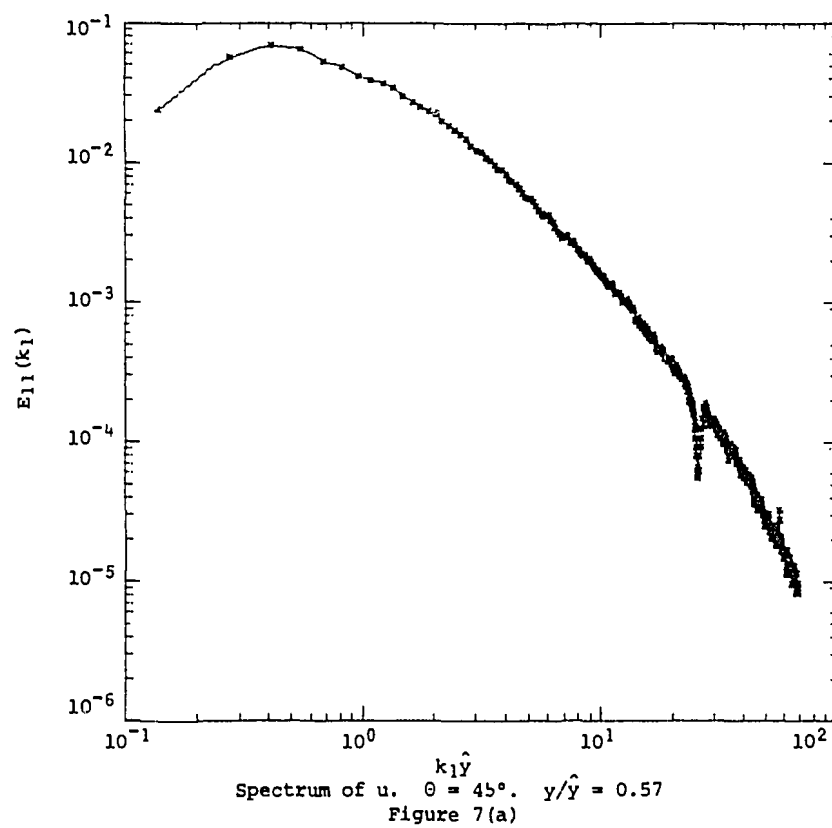
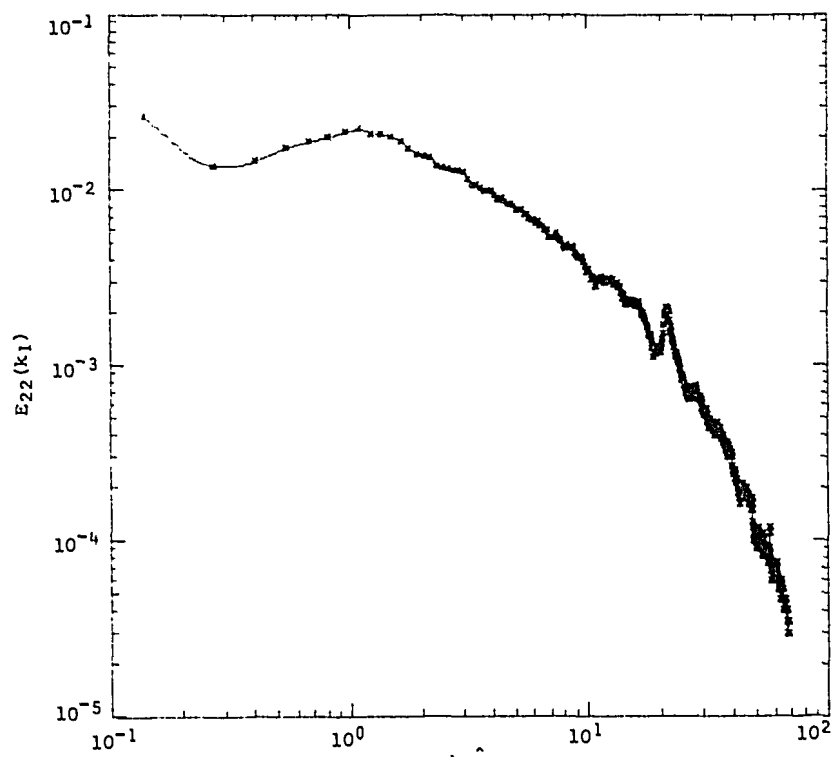
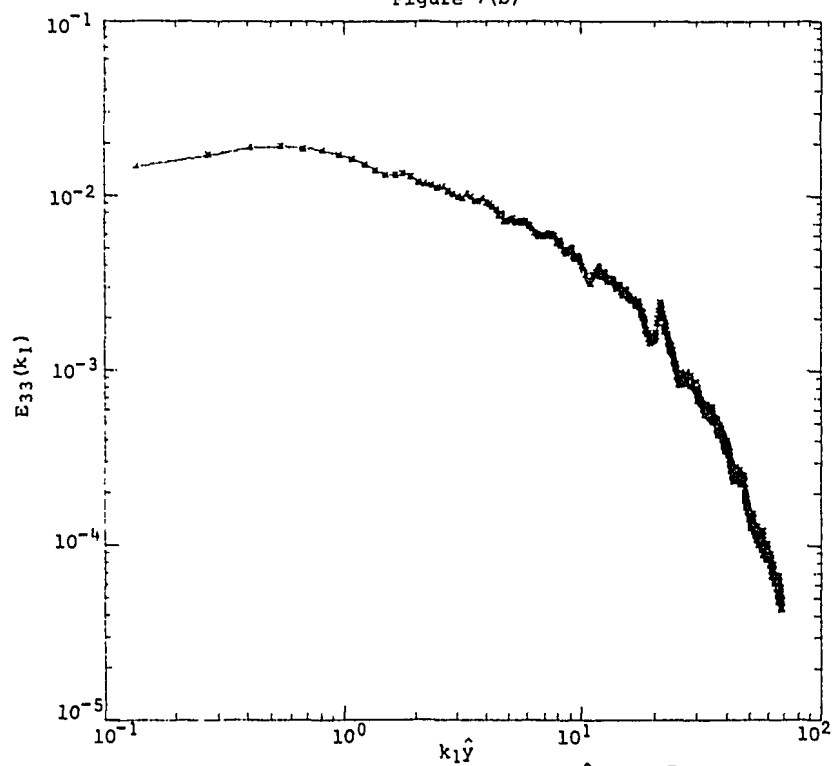


Figure 6





$k_1 \hat{y}$
Spectrum of v . $\theta = 45^\circ$. $y/\hat{y} = 0.57$
Figure 7(b)



$k_1 \hat{y}$
Spectrum of w . $\theta = 45^\circ$. $y/\hat{y} = 0.57$
Figure 7(c)