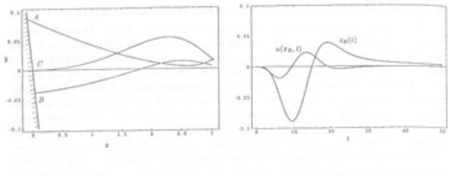

(a) (b)

Figure 2: (a) Illustrative wave profiles evolved from an initial internal water elevation; — C, initial profile at time $t = 0$, — A, Maximum run-up, — B, minimum run-down; (b) An illustrative plot of time history of the run-up position $x = x_R(t)$, and fluid velocity, $u(x_R, t)$.

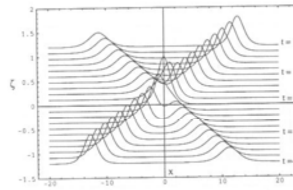

Figure 3: Head-on collision of two solitons with amplitudes $a_+ = 0.6$ and $a_- = 0.3$, for time $-10 < t < 10$.

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REVIEW OF TURBULENCE RESEARCH IN CHINA

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ABSTRACT Turbulence research has been emphasized in China since 1980's on both fundamental and applied areas. In this paper the author will present the major contributions of turbulence research made by Chinese scientists in last decade and prospect its furher development.

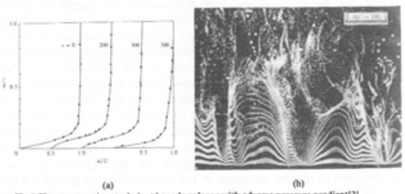
1. Introduction

Turbulence is one of the extremely difficult topics in fluid mechanics. It attracts a large number of scientists to make long lasting efforts for exploring its nature. Considerable progress has been achieved in last few decades, but there is still a long way to fully understand, precisely predict and effectively control turbulent flows. On the fundamental side the discovery of coherent structures shed new lights on the nature of turbulent shear flows forty years ago, and people expected that they would break through the unpredictable barrier of turbulence. Indeed the discovery of coherent structures is the significant progress in turbulence research such that the coherent structures dominate the generation of turbulence in various shear flows and there are a number of devices for turbulence control based on the management of the coherent structures. However the dynamics of the coherent structures is not well understood for their complexity. One can not completely succeed in control of turbulent flows when they do not fully understand the flow nature. And also it is not so clear how to predict the turbulent flows by use of the knowledge of coherent structures. On the theoretical side the chaos in nonlinear dynamics and fractal geometry in topological analysis of the flows give rise to the some new ideas on the turbulence, however they are conceptual but not constructive. The rapid development of modern computer in last two decades has provided a powerful tool for turbulence study and it is a great hope for the deep understanding and accurate prediction of turbulent flows by means of modern computers. There are a number of available data banks of direct numerical simulation of simple turbulent flows for detailed studies of the structures and properties of those flows, for instance the examination of the turbulence models and investigation of the

coherent structures have been conducted with considerable success. Unfortunately the most powerful computer available today can only deal with simple turbulent flows and it may not be realizable for simulating complex turbulent flows in practice until the middle of next century. On the applied side prediction and control of turbulent flows is of great importance in engineering and natural environment. A number of refined turbulence models have been proposed in last few decades which succeeded in prediction of some complex turbulent flows, however engineers still feel unconfident of available turbulence models because of their non-universality. In this paper the author will present the major contributions in turbulence research made by his Chinese colleagues and himself in last decade and prospect its further development.

2. Exploration of the coherent structures of turbulent flows

It is now believed that the coherent structures in turbulent shear flows are the dominant events in generation of turbulence and the understanding of their nature is the basis of the control and management of turbulent flows. They may also give some clues to the turbulence models. In last decade some Chinese scientists paid considerable attention to explore the structures in more or less complex turbulent shear flows, for instance the plate turbulent boundary layer with pressure gradients[1,2] and turbulent flows over curved walls [3,4] etc., Great efforts were also made for searching the detailed structural features in turbulent boundary layers, wakes and mixing layers.[5,6,7,8] Lian (1985,1990) investigated the coherent structures in a plate turbulent boundary layer with pressure gradients by means of hydrogen bubble technique. He found that the low-speed streaks are wider in the near wall region of turbulent boundary layer with adverse pressure gradients in the region of incipient separation, as shown in Fig. 1a and Fig.1b.



(a) (b)

Fig.1 The structure in a turbulent boundary layer with adverse pressure gradient[2]
(a) the velocity profiles (b) the hydrogen bubble lines at x=200mm, $y^+ = 12$

The streak structures in the turbulent boundary layer with adverse pressure gradient has the peculiar features such that (1) the long streaks downstream along the interface between low-speed and high speed regions are continually stretching and their speed may be greater than the high speed bubble lines; (2) The streamwise vortices are developed along the interfacial region;(3) the transverse vortices are observed at the front of the high-speed regions, see Fig.2 and Fig.3 respectively.

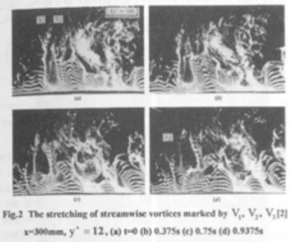


Fig.2 The stretching of streamwise vortices marked by V_1, V_2, V_3[2]
x=300mm, $y^+ = 12$, (a) t=0 (b) 0.375s (c) 0.75s (d) 0.9375s

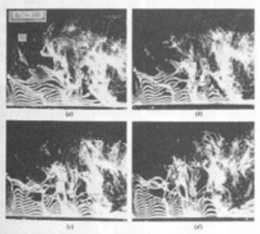


Fig.3 A transverse vortex visualized at the front of a high-speed region, marked by V
x=300mm, $y^+ = 12$, (a) t=0 (b) 0.1875s (c) 0.375s (d) 0.5625s

The author has been interested in the turbulent flow over curved wall and utilized the hydrogen bubble technique, LDV and particle tracking method to explore the structures on both convex and concave walls in considerable details.[3,4] The author found that the streak structures, which were believed to be longitudinal vortices, are intensified on concave wall when turbulent flow is entering to the concave wall, while the structure is weakened when it is approaching to the convex wall and will disappear totally beyond some turning angle, say over 45°, the visualized pictures are shown in Fig.4.

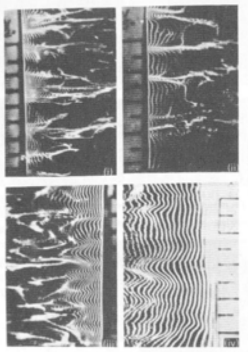


Fig.4 The streak structure at concave and convex wall (Re=5000, $y^+ = 5$)[3]
(i) concave 15°, (ii) concave 67.5° (iii) convex 15° (iv) convex 67.5°

The curved wall effects has been also studied by conditional sampling of the velocity fluctuations such that the average burst frequency, detected by the VITA scheme, is greater at the concave wall than that at the convex wall. In previous investigation the geometrical patterns of the coherent structures were qualitatively visualized and the dynamical properties were detected by conditional samplings based on the measurements of single-point time series. However the coherent structures are of time-spatial events. To record the time series of velocity field in two dimension the author developed a novel particle tracking device by means of an oscillating laser beam and processed the image records on

computer by which the two dimensional spatial correlation contours were obtained as shown in Fig.5 which demonstrates the elongated and asymmetrical correlation in streamwise direction at concave wall whereas the two dimensional correlation is near circular at convex wall. These indicate that there is longitudinal streaky structure at the concave wall and nothing at convex wall.

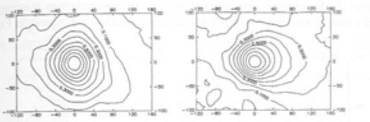
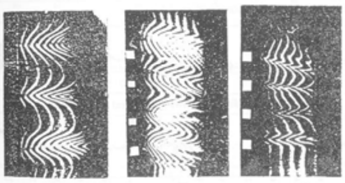


Fig.5 The two dimensional correlation $R_{uu}(\xi,\zeta)$ at concave wall and convex wall[4]
Re=2500, $y^+ = 15$, left: convex wall 45°, right: concave wall 45°

The response of the external disturbances in the turbulent shear flows is of great interest in both understanding of the dynamic properties and control of the turbulent structures. Su and his students investigated the influence of external disturbances on the coherent structures in both turbulent boundary layer and mixing layer in a water tunnel.[5,6] The influence of disturbances on the turbulent structures at the turbulent boundary layer was investigated by injection or suction of fluid through small holes on the plate and the near-wall structures were visualized by hydrogen bubble technique. They found that the suction caused the low-speed region to be wider, in contrast the injection made the low-speed streak sharpened, as shown in Fig.6.



(a) (b) (c)
Fig.6 The influence of injection and suction on the near-wall structure[5]
(a) without disturbances (b) with suction (c) with injection

The results show that the suction is similar to the sweep event in the burst cycle and injection simulates the ejection event. The reduction of turbulent skin friction is usually resulted from the suction and the intensification of turbulence is caused by the injection, the flow structures is changed greatly by the near-wall disturbances. Su and Yao also studied the influence of sinusoidal disturbances in the outer layer on the structures near the wall. The sinusoidal disturbances were put into the flows by a vibrating ribbon. The average spanwise spacings of the streaks and the bursting frequency are changed remarkably as shown in Fig. 7.

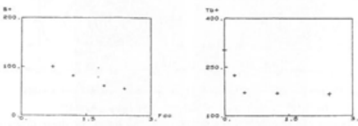


Fig.7 The change of coherent structure by external disturbances $f_{d\delta} = f_d\delta / U_\infty$[5]
left: average spacing of the streaks $s^+ = \lambda u_\tau / \nu$, right: average period of bursts $T^+ = Tu_\tau^2 / \nu$

Su and Zhang(1990) have investigated the influence of external disturbances on the mixing layer by means of a vibrating ribbon. They found that the vortical pairing patterns are dependent on the composition of the disturbances. Fig.8 shows that the two vortices are pairing when the disturbances are composed of the primary frequency $\varpi_0 = 2\pi f_0 \theta / U_m = 0.225$ and its harmonics $\varpi_0 / 2$, where θ is the momentum thickness of the mixing layer and U_m is the mean velocity of the layer, whereas four vortices pairing appears in the composition of the primary disturbance plus its harmonics of $\varpi_0 / 4$.

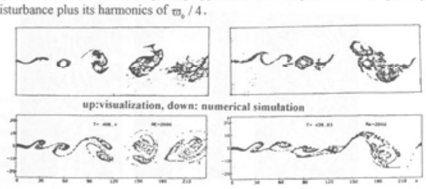
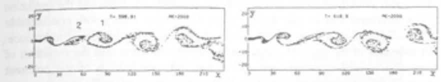


Fig.8 The vortex pairing in mixing layer with sinusoidal disturbances, up:visualization, down:numerical
left: primary ϖ_0 plus harmonics $\varpi_0 / 2$, right:primary ϖ_0 plus harmonics $\varpi_0 / 4$

They also found that the vortical patterns are dependent on the phase differences between the primary disturbance and it harmonics. Fig.9 shows the vortex tearing in the evolution of the vortical patterns, i.e. vortex 2 marked in the Figure, the phase difference is $\pi / 2$ between the primary disturbance ϖ_0 and its harmonics $\varpi_0 / 2$.



(a) (b)
Fig.9 the change of vortical patterns due to phase differences[6]
(a) beginning of vortex tearing (b) after vortex tearing

Wei(1994) investigated the response of the acoustic excitation on wake flows behind an axisymmetrical blunt body . He found the phase lock-in phenomena in the turbulent wake, as shown in Fig.10 such that the spectrum of the turbulent fluctuation will be locked in the forced frequency, f_e, between 40 to 70 Hz while the frequency of the vortex shedding, f_s, is around 20 Hz to 70Hz.

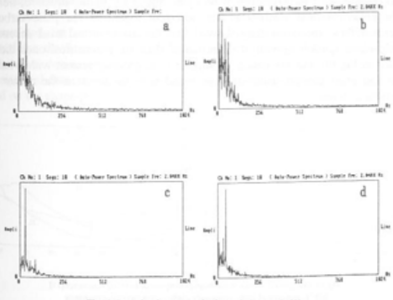


Fig.10 Lock-in phenomena in the turbulent wake[8]
(a) f_s =43 f_e=0, (b) f_s=20, f_e=20, (c) f_s=30, f_e=30, (d) f_s=40, f_e=40

3. Theoretical models of the coherent structures

The coherent structures are thought as organized motions, however it is not easy to recast the structure analytically since their trigger and scales are at random. A few attempts to model the coherent phenomena have been made with partial success. The emergence of coherent structures in turbulent free shear layer, e.g. mixing layer, jets and wakes etc., is usually interpreted as the instability of their mean velocity profiles, which contain an inflectional point and the evolution of the structures can be calculated by weak nonlinear theory with considerable success(Liu,1989).[9] However the detailed generation mechanism of turbulence, the influence of the external disturbances on the structures and the evolution of three dimensional structures remain unclear. The explanation of the coherent structure in wall-bounded turbulent flows is even more difficulty, the mean velocity profiles of these flows are stable under linear perturbation. In early 1980's the author (Zhang and Lilley,1982)[10] interpreted the trigger of longitudinal vortices at near-wall region as a direct resonance between Tollmien-Schlichting waves and transverse vorticity disturbance by means of a semi-analytical approach. The theoretical interpretation of the coherent structures is indeed a tough target, however using weakly nonlinear theory Zhou and his co-workers published a number of encouraging results. They found that approximate triad resonance of three primary waves can induce the streak structure, i.e. the trace of longitudinal vortices in the near-wall region of the plate turbulent boundary flow, moreover they showed that the asymmetrical triad resonance would cause quicker growth of disturbances than the symmetrical ones did, as shown in Fig.11. The theoretical prediction is in good agreement with what Su, Lian and other foreign scientists have found in experiments as the author has mentioned above.

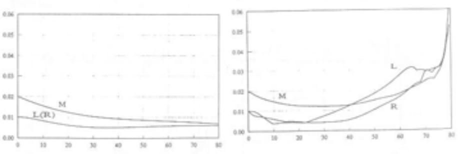


Fig.11 The growth of the disturbance component in triad resonance[11]
left: symmetrical triad resonance right: asymmetrical resonance

Assuming a complex eddy viscosity in stability analysis Zhou and Luo[12] were able to simulate the outer structure of wall-bounded turbulent flows, the

comparison of the predicted flow patterns with those measured by Antonia[13] is shown in Fig.12 with satisfaction.

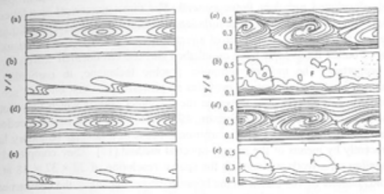


Fig.12 The simulation of the flow pattern in the outer layer of turbulent boundary layer
left: Theoretical prediction by Zhou and Luo[12], right: Measurements by Antonia[13]
(a),(d) streamlines, (b),(e) vorticity contours. (a) Re=11800,(b) Re=19005,(d) Re=47949,(e) Re=84427

Zhou has shown that the assumption of shape-preservation is incorrect in weakly nonlinear evolution of the disturbances. With consideration of the deformation of flow modes for primary and high-harmonic disturbances Zhou and Ma[14] reformulated the weakly nonlinear evolution problem for mixing layer and showed the developments of disturbances in both large and small scales. The results are demonstrated in Fig.13 in which the better agreements with experimental data are shown in comparison with the weakly nonlinear analysis based on the shape-preservation assumption.

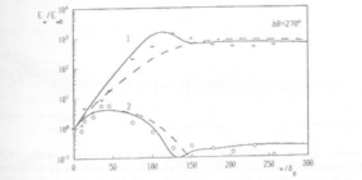


Fig.13 The development of disturbance energy curve 1 ϖ_1, curve 2 ϖ_2
—calculated by Zhou et.al.[14], ---calculated by Liu[9], +,o measured by Ho[15]

4. Direct numerical simulation of turbulent flows

The direct numerical simulation of Navier-Stokes equation is an ideal method for understanding of the transition of laminar to turbulent flows and the properties of fully developed turbulent flows as well. The direct numerical simulation of turbulence has been emphasized in turbulence community and developed quickly during last two dacades. A number of directed numerical simulated databanks of typical turbulent flows have been established and used in detailed search for the flow properties. The modern computer graphic technique, in particular the computer animated visualization, provides so powerful tool that one can see the individual events in turbulent flows on the computer screen which may not be seen in physical experiments. (Robinson, 1991) [16]. Shi(1994) has succeeded in the direct numerical simulation of transition process of a laminar boundary layer flow recently by means of the pseudo-spectral method.[17] They completed the computation on a work-station with the spatial resolution of 32 × 32 × 48 at the Reynolds number of 407 based on the boundary layer thichness, the emergence of counterrotating vortices and high shear layer, i.e. spikes, are shown in Fig.14 with comparison to the measurement by Kovasznay. [18]

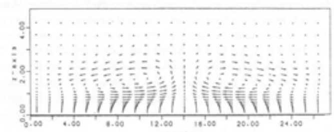


Fig.14a The velocity vector in the cross section at time 1350H / U_0

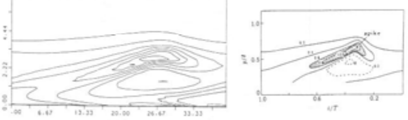


Fig.14b The high-shear layer in the transition of channel flow at time 1425
left numerical simulation by Shi et. [17] al. right measurement by Kovazsny[18]

Xu and Zhang(1995) have completed a direct numerical simulation of a turbulent channel flow at Reynolds number 5000 in cooperation with the

Laboratory for Aero and Hydrodynamics at Delft University of Technology in the Netherlands. Under careful consideration of the numerical databank Xu and her Dutch colleagues found an important event, which has been ignored by previous investigators. The newly found event is a number of strong pulses of transverse fluctuations which occurs in the near wall region, i.e. $y^+ < 10$, and results in a flatness as great as 22. The typical strong pulse is shown in Fig.15, which clearly demonstrates the quick decay of the pulses away from the wall.

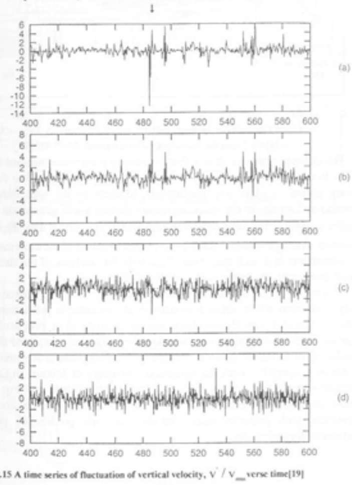


Fig.15 A time series of fluctuation of vertical velocity, v' / v_{rms} verse time[19]
strong pulse noted by an arrow, (a) $y^+ = 2.54$, (b) $y^+ = 11.6$, (c) $y^+ = 47.6$, (d) $y^+ = 168$

The strong pulse event are always occurring at the edge between the high and low-speed regions and lasting quite long time as illustrated in Fig.13.

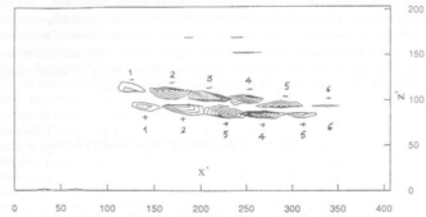


Fig. 16 The motion of the strong pulses, $+ v / v_{rms} > 5$ and $- v / v_{rms} < 5$[19]
indices denote the time series, the time interval $\Delta t = 0.4H / U_m$

The detailed analysis shows that the strong pulses are induced by the sweep event from the outer layer and followed by an ejection, thus the findings of the strong pulses of transverse fluctuations adjacent to the wall indicate that the ejection and sweep in the inner region are indeed a self generation process. The results imply that the very near wall region, i.e. $y^+ < 10$, is also important for the coherent structure which is not well explored because of the extremely difficult in measurements in a such thin layer. Hopefully the analysis of the data bank of the direct numerical simulation will give us fruitful answer.

An alternative to the direct numerical simulation of turbulence is the Large eddy simulation which needs less storage of computer in prediction of turbulent flows of great Reynolds numbers and is thought as a practical method for engineering applications in next decades. Su(1992) has completed the large eddy simulation of turbulent flows in straight and curved duct at Reynolds number of 49000 in cooperation with the Technical University of Munich in Germany. The simulated results are shown in Fig.17 for a straight duct and Fig.18 gives the simulated results of the turbulent flow in a curved duct. The results are in better agreement with previous measurements than any predictions performed by phenomenalogical models.

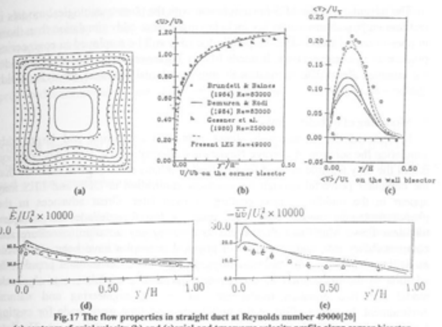


Fig.17 The flow properties in straight duct at Reynolds number 49000[20]
(a) contours of axial velocity (b) and (c)axial and trnasverse velocity profile along corner bisector
(d) and (e) profile of turbulence energy and Reynolds stress along corner bisector

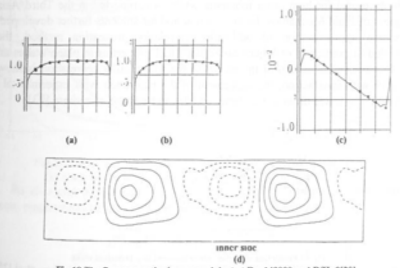


Fig.18 The flow properties in a curved duct at Re=149000 and R/H=9[20]
(a)profiles of axial velocity<u>, (b) profile of <ur>, (c)profile of Reynolds stress
(d) the streamlines of the secondary flow, —Su's calculation, · Eskinazi and Yeh's measurement [21]

The advantage of the LES in comparison with the phenomenological models is that less empirical parameters are included in the large eddy simulation than those in phenomenological models. Hopefully the LES will be employed in engineering practice in the next century. It needs further improvement in the subgrid model for complex flows and in near wall regions of real flows at great Reynolds numbers etc.

5. Modelling of turbulent flows

In spite of the advances in direct numerical simulation and large eddy simulation the solution of average Navier-Stokes equation, i.e. Reynolds equation, is still the only feasible method for practical problems since experts estimate that the computer powerful enough for practical application in DNS and LES may appear in the middle of next century or even later. Great advances in the phenomenological models have been made in last few decades for complex turbulent flows which include the effects of buoyancy, rotation, curvature and compressibility etc., and a number of physical principles have been set up for modelling. In other words the modern models are more rational and popular. In addition to the application of conventional turbulence models , e.g. algebraic model and two equation model etc., in various engineering and natural environment the major effort of the turbulence modelling were made for casting higher order moment closure and nonlinear closure of second moment. The latq famous scientist Professor P.Y. Chou at Peking University developed a quasi-similarity model for high order moments which was reported in the Third Asian Congress of Fluid Mechanics. Later on Chou and his students further developed a successive approximation of odd-order correlation truncation method, they succeeded in prediction of higher order statistical properties in plane wakes and jets. A critical examination of the model in the fourth order correlation is shown in Fig.19 with satisfaction, the agreement of the prediction with experimental is much better in lower order correlations which can be found elsewhere.[23]

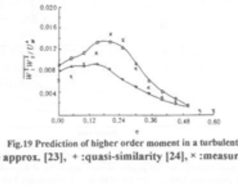


Fig.19 Prediction of higher order moment in a turbulent wake
O: successive approx. [23], + :quasi-similarity [24], × :measured by Chou et al.[25

Fu(1994) at Tsinghua University developed nonlinear formulation of second moment closure, i.e. the Reynolds stress model. For instance, the return to isotropy process in redistribution of Reynolds stress is usually closed by Rotta formula, which is a linear isotropic closure scheme. However modern tests of the turbulence decay indicate that the return to isotropy is a nonlinear process. Fu proposed a nonlinear closure of the return to isotropy term as follows,

$$\phi_{ij} = -\beta \varepsilon b_{ij} + \gamma (b_{ip} b_{pj} - \frac{1}{3}\delta_{ij} b_{pp}^2)$$

The first term is the original Rotta formula. Usually the coefficients β and γ are the functions of the second and third invariants of b_{ij}. Fu has proved that the β and γ must satisfy the relation as/

$$\gamma = 3(\beta - 2).$$

Applying the nonlinear closure for return to isotropic process Fu predicted the decay of anisotropic turbulence, the calculated second and third invariants of the distorted isotropic turbulence are shown in Fig.20 in which the predictions with different models are also presented for comparison and the better agreement with the experimental results is obtained by use of the nonlinear closure.

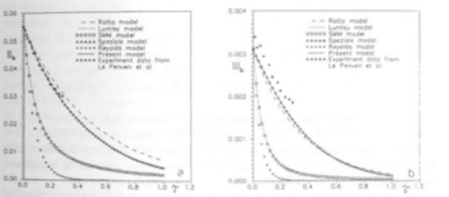


Fig.20 Anisotropy invariants after plane distortion with initial III>0[26]
(a) decay of the second invariants, (b) decay of the third invariants

Fu also cast a nonlinear model for the turbulence diffusion which has not been emphasized before. Fu proposed the diffusion as follows

$$d_{ij} = \frac{\partial}{\partial x_k}\left[c_s \frac{k}{\varepsilon}\left(\overline{u_k u_l} \frac{\partial \overline{u_i u_j}}{\partial x_l} - 0.4\overline{u_i u_l}\delta_{jk}\frac{\partial k}{\partial x_l} - 0.4\overline{u_j u_l}\delta_{ik}\frac{\partial k}{\partial x_l} \right)\right]$$

Applying the nonlinear diffusion to the turbulent jet problem Fu clarified the jet paradox of turbulence modelling such that the spreading rate of the round jet is much higher than that of the plane jet by use of the basic Reynolds stress model without tuning the model parameters. The results are shown in Table 1 and Fig.21-Fig.22.

Table 1 The spreading rates of plane and round jets

Flow type	Basic RSM	Fu's model[27]	Experimental
plane jet	0.116	0.103	0.110[28]
round jet	0.129	0.0949	0.094[29]

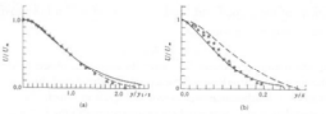


Fig.21 Self-preserving velocity profiles
(a) plane jet, (b) round jet, ---Basic RSM, —Fu[27] measurements •: [28]

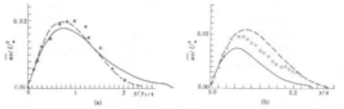


Fig.22 Self preserving profiles of the turbulent shear stress
(a) plane jet, (b) round jet, ---Basic RSM, —Fu[27], •: [28], O:[29]

It is evident that the improvement in the closure of turbulence diffusion with inclusion of pressure-velocity correlation resolves the jet paradox of turbulence modelling.

The major shortcomings of the phenomenological models is the problem of universality. There are a number of turbulence models proposed by authors with good testing examples of some kind of flows but they fail to predict other flows with satisfaction. To my belief there might be no universal turbulence model at all based on the Reynolds statistics. It is inevitable to modify the models from flows to flows. However it might be able to construct the individual models for typical flows if we can catalog the turbulent flows into a number of typical regimes. This is so-called zonal modelling strategy and the author believes that it will resolve the non-universality problem. A number of local modifications of the turbulence

modelling were tried by some Chinese scientists with considerable success. Zhang established a near wall modelling for the second moment closure, the author proposed a curvature modification of k- ε model and a matching method for the zonal modelling of second moment closure. The details of those approaches can be found elsewhere.[30,31,32]

Before switching to the last part of the presentation the author should apologize for being unable to include all contributions made by the Chinese scientists because of the personal limitation of the knowledge.

6. Prospect for the further development in turbulence research

Although the scientists in turbulence community made great effort for the turbulence research over one hundred years they still do not meet the demands in engineering and natural environment. We are far away from full understanding of the turbulence nature. It may take quite long time to achieve the tough task, since turbulence is an astonishingly complex nonlinear motion in infinite dimension. However I am not pessimistic, the progress in turbulence research in the past decades did shed lights on the exploration of turbulence and we are now on the way to further break the secret of the turbulence step by step.

In reality the author expects that development of the turbulence research will be achieved in the following areas in next decades. The coherent structures of turbulent shear flows will still be emphasized in close links with control of turbulent flows to reduce drag and noise. The detailed dynamical properties in different parts of the coherent structures may give some clues to cast zonal turbulence models. The direct numerical simulation of turbulent flows will be further improved in parallel to the development in modern computer, the major role of DNS in turbulence research is to explore the fundamental nature of simple or less complex turbulent flows in foreseeable future. The computer visualization will play an important role in DNS, in particular computer animation. The large eddy simulation of turbulent flows will be used in engineering practice with the improvement in the subgrid models and numerical schemes, e.g. the finite difference scheme with higher accuracy. The phenomenological models will be still dominant in prediction of turbulent flows in engineering practice, improvement of the models will be in close cooperation with modern computational fluid dynamics, for instance the multi-grid techniques and parallel algorithm will be adopted in collaboration with zonal modelling. On the theoretical side of turbulence research the nonlinear dynamical system is the key to understand the nature of turbulence, the progress in the study of chaos and fractal geometry will help us to understand turbulence, however we are expecting mathematicians to break through the infinite dimension barrier.

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References

[1]Lian, QX Acta Mechanica Sinica (in English)**1**:71,1985
[2]Lian, QX JFM **215**, 101, 1990
[3]Zhang, ZS and Wang Xilin Acta Mechanica Sinica (in English)**3**:1, 1989
[4]Zhang ZS et al. Applied Scientific Research , **51**:249, 1993
[5]Yao, SH and Su, W Acta Mechanica Sinica (in Chinese) **23**:385, 1991
[6]Zhang, HQ and Su, W Acta Mechanica Sinica (in Chinese) **21**:288, 1989
[7]Su, W and Sun, GH Acta Mechanica Sinica (in Chinese) **26**:121, 1994
[8]Wei ZL Proc. Sino-Japan workshop on turbulent flows, Beijing, China, p312 1989
[9]Liu, J.T.C. Ann. Rev. Fluid Mechanics **21**:285, 1989
[10]Zhang, ZS and Lilley, GM Turbulent Shear Flows III p60, 1982
[11]Zhou, H and Xiong ZM Science in China (in English) **24**:941, 1994
[12]Zhou, H and Luo, JS Sino-Japan workshop on turbulent flows, Beijing, China p359, 1994
[13]Antonia, RA, et al. JFM **213:**267, 1990
[14]Zhou, H and Ma, L (to be published in Science in China) 1995
[15]Ho, CM and Huang, IS JFM **119**:443
[16]Robinson, SK Ann. Rev. Fluid Mechanics, **23**:601,1991
[17]Shi, XG Proc. Sino-Japan workshop on turbulent flows, Beijing, China, p229, 1994
[18]Kovazsnay, LS et al. Proc. 1962 Heat Transfer and Fluid Mechanics. p1
[19]Xu, CX and Zhang, ZS Proc. National Congress on Fluid Mechanics, Beijing, China, 1995
[20]Su, MD Proc. Sino-Japan workshop on turbulent flows, Beijing, China, p258, 1994
[21]Eskinazi, S and Yeh, H J. of Aero. Sci. **23**:23, 1956
[22]Chou, PY Proc. Third Asian Congress of Fluid Mechanics, Tokyo, Japan, 1986
[23]Lin JZ and Huang, YN and Chou, PY Acta Mechanica Sinica (in Chinese) **26**:643, 1993
[24]Chou, PY and Chen, S Science in China **4**:369, 1987 (in English)
[25]Chou PY and Lin JZ and Wei, ZL J. of Hydrodyanmics **3**:1, 1991(in English)
[26]Fu, S Proc. Sino-Japan workshop on turbulent flows, Beijing, China, p42, 1994

[27]Fu, S Acta Mechanica Sinica (in English) **8**:208, 1992
[28]Taulbee DB et al. Proc. Sixth Symp. on Turbulence Shear flows, Toulouse, France, 1987
[29]Ramaprian, BR et al. ASME J. of Fluid Engng. **107**:2641985
[30]Zhang, GH and Xiong, GH Proc. Sino-Japan workshop on turbulent flows, Beijing, China, p321,1994
[31]Zhang ZS and Shan, HSino-Japan workshop on turbulent flows, Beijing, China, p343,1994
[32]Xia, JY and Zhang ZS Acta Aerodynamica Sinica, **8**:136, 1990(in Chinese)