HYDRODYNAMIC INTERACTION AND MIXING MECHANISMS OF PARALLEL FLUID STREAMS

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Abstract: The mixing of two flat flows is a fundamental concept in fluid dynamics with numerous applications in engineering and environmental sciences. This paper investigates the mechanics, efficiency, and theoretical principles of the mixing process in two-dimensional (2D) flows. Emphasis is placed on understanding the physical behavior of the mixing process, its mathematical modeling, and its practical implications. The study aims to enhance the predictability and controllability of flat flow systems in various industrial and environmental scenarios. The results highlight factors affecting flow stability and mixing efficiency and suggest improvements for optimizing such processes.

Keywords: Flat flows, two-dimensional mixing, fluid dynamics, vortex dynamics, Reynolds number, shear flow, turbulence, laminar flow.

ГИДРОДИНАМИЧЕСКОЕ ВЗАИМОДЕЙСТВИЕ И МЕХАНИЗМЫ СМЕШЕНИЯ ПАРАЛЛЕЛЬНЫХ ПОТОКОВ ЖИДКОСТИ

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Аннотация: Смешивание двух плоских потоков является фундаментальной концепцией в гидродинамике и имеет многочисленные приложения в инженерии и экологических науках. В данной работе исследуются механизмы, эффективность и теоретические принципы процесса смешивания в двухмерных (2D) потоках. Особое внимание уделено пониманию физических особенностей процесса смешивания, его математическому моделированию и практическим последствиям. Цель исследования - улучшить предсказуемость и управляемость плоскими потоками в различных промышленных и экологических ситуациях. Результаты подчеркивают факторы, влияющие на стабильность потока и эффективность смешивания, и предлагают улучшения для оптимизации таких процессов.

Ключевые слова: Плоские потоки, двухмерное смешивание, гидродинамика, динамика вихрей, число Рейнольдса, сдвиговой поток, турбулентность, ламинарный поток.

PARALLEL SUYUQLIK OQIMLARINING GIDRODINAMIK O‘ZARO TA’SIRI VA ARALASHISH MEXANIZMLARI

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Annotatsiya: Ikki tekis oqimning aralashishi suyuqlik dinamikasida asosiy tushuncha bo'lib, muhandislik va atrof-muhit fanlarida ko'plab ilovalarga ega. Ushbu maqolada ikki o'lchovli (2D) oqimlarda aralashish jarayonining mexanikasi, samaradorligi va nazariy asoslari o'rganiladi. Aralashish jarayonining jismoniy xatti-harakatlarini tushunishga, uning matematik modelini yaratishga va amaliy ahamiyatini o'rganishga alohida e'tibor qaratilgan. Tadqiqotning maqsadi turli sanoat va ekologik holatlarda tekis oqim tizimlarini prognoz qilish va boshqarishni takomillashtirishga qaratilgan. Natijalar oqim barqarorligi va aralashish samaradorligiga ta'sir qiluvchi omillarni ta'kidlaydi va bunday jarayonlarni optimallashtirish uchun takliflar keltiradi.

Kalit so'zlar: Tekis oqimlar, ikki o'lchovli aralashish, suyuqlik dinamikasi, vanta dinamikasi, Reynolds soni, kesish oqimi, turbulensiya, laminar oqim.

Introduction

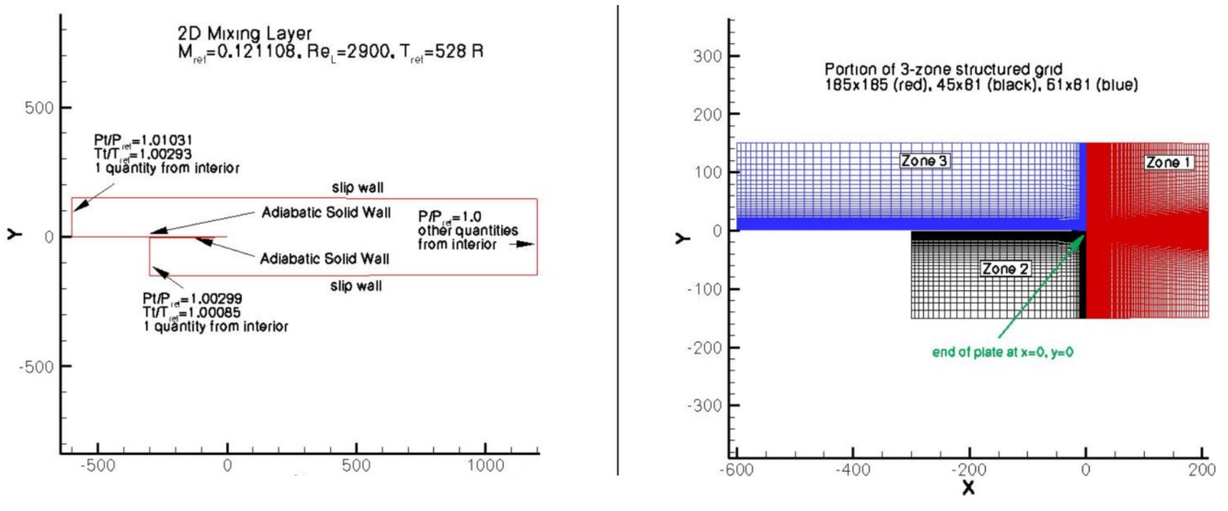
Mixing processes are vital in many natural and industrial contexts, ranging from chemical engineering to environmental flow systems. Specifically, the mixing of two flat, two-dimensional flows (also referred to as planar flows) is of interest in various sectors, such as microfluidics, combustion, and air-pollution control. A flat flow refers to fluid motion constrained within a plane, where the flow variables depend only on two spatial coordinates, making it an idealized but instructive model for real-world applications.

The efficiency of mixing in such systems is governed by a variety of factors, including the velocity gradients between the two flows, the flow's initial conditions, and the physical boundaries involved. Viscous diffusion, advection, and turbulence all play crucial roles in how effectively two flows merge. This paper aims to analyze the theoretical aspects of mixing in flat flows, model the process mathematically, and identify key parameters that enhance or hinder the mixing efficiency.

The dynamics of mixing involve the interaction of shear layers, the generation of vortices, and the development of instabilities that promote flow uniformity over time. These phenomena can be modeled using fundamental fluid mechanics principles, particularly the Navier-Stokes equations. Depending on the nature of the flows involved-whether laminar or turbulent-the characteristics of mixing can vary significantly, and this paper aims to cover both regimes.

A mixing layer is formed when two fluid streams with different velocities or densities contact each other. The interface between two fluids is subject to complex flow phenomena such as turbulence, mixing and swirl. Understanding and accurate prediction of the behavior of the mixing layer is important in a variety of applications including combustion, chemical reactions, and flows in surrounding medium. In the framework of the two-fluid model, this problem was solved numerically in [32]. However, in that article, the control volume method and the *SIMPLE* algorithm were used for the numerical solution.

This problem was well studied experimentally. In the experiment, a 3 mm thick separating plate in a 300 mm wide tunnel was used. The end of the plate is located at the point x = 0, and two fluid flows with different velocities merge below this point. The plate is modeled with a taper starting at x = -50 mm and ending with a trailing edge thickness of 0.3 mm at x = 0. In the experiment, the upper high-velocity flow has a boundary layer thickness of about 9 .6 mm at x = -10 mm (near the trailing edge of the plate) and a pulse thickness of about 1 mm. The lower flow with lower velocity has a boundary layer thickness of about 6.3 mm and a pulse thickness of about 0.73 mm. The Reynolds number based on L (1 mm, which corresponds to the length of "1" grid) is 2900. The temperature of the airflow is T_{ref} = 293, K = 528 R and the velocity of sound a_{ref} = 343 m/s. The static pressure p_{ref} is equal to atmospheric pressure (101325 Pa). Free stream velocities are 41.54 m/s at the top and 22.40 m/s at the bottom. If this is applicable to the particular turbulence model, this case should be considered with a low level of free stream turbulence. In the experiment, Tu was about 0.3%. The boundary conditions are shown in Fig. 10a, and an illustration of the computational grid and computational domain is shown in Fig. 10b.



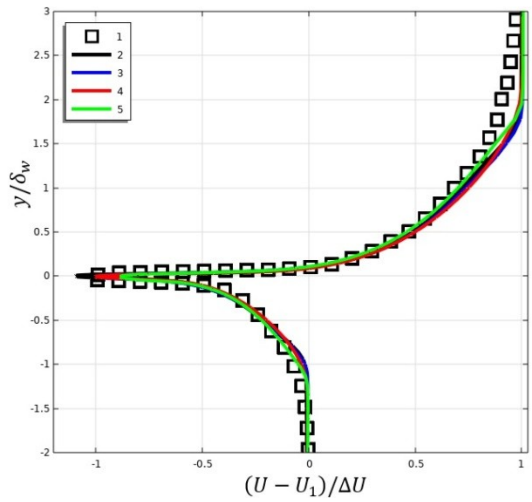
a) b)

Fig. 10. 2D Mixing layer. a) boundary conditions and b) computational grid and

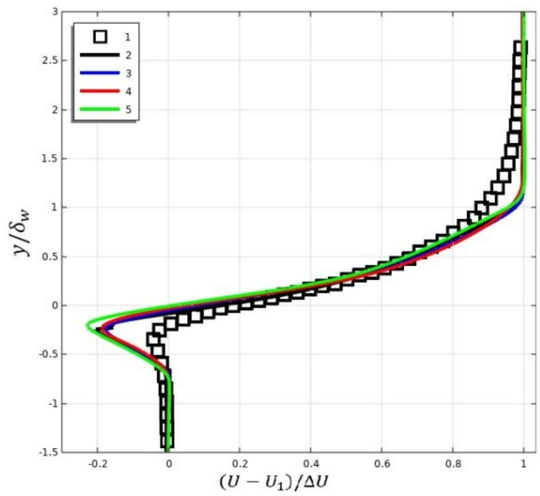
area.

In Fig. 10, P_t refers to total pressure, P refers to static pressure, and T_t refers to total temperature.

Figure 11 shows graphs of the dimensionless longitudinal velocity in various sections of the channel based on the results of turbulence models. Experimental data are also given for comparison. The figures show the profiles of the axial U-velocity component in different sections of the channel. Here U_1=22.40 m/s, ΔU=19.14 m/s and δw=5.236 mm at x=1 mm, δw=8.85 mm at x=50 mm, δw=13.771 mm at x=200 mm, δw=35.894 mm at x=650 mm, and δw=50.547 mm at x=950 mm.



a)



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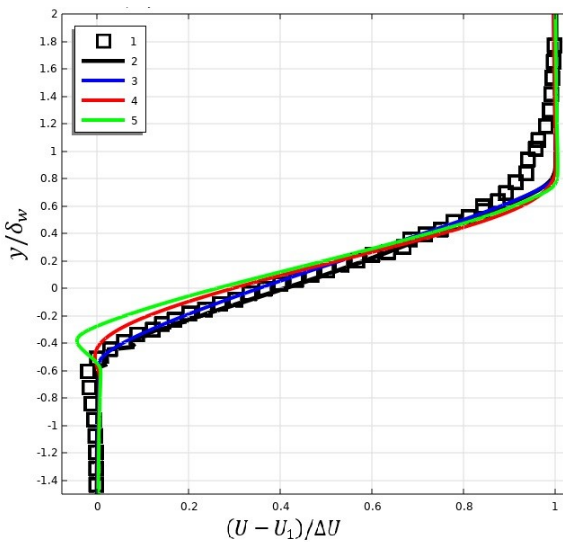

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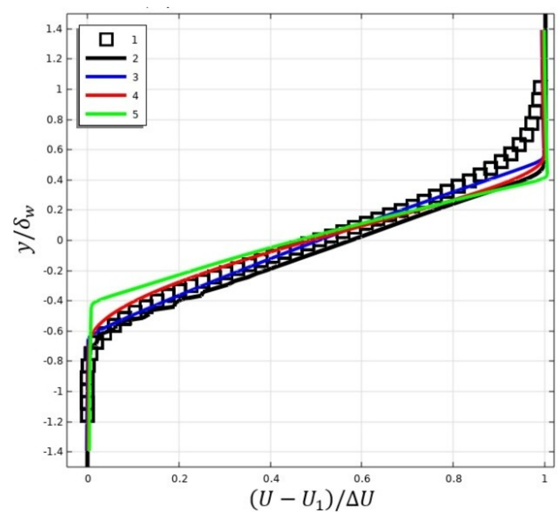

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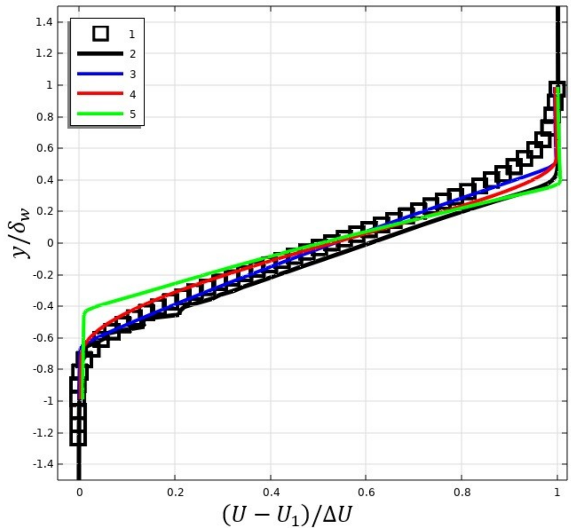
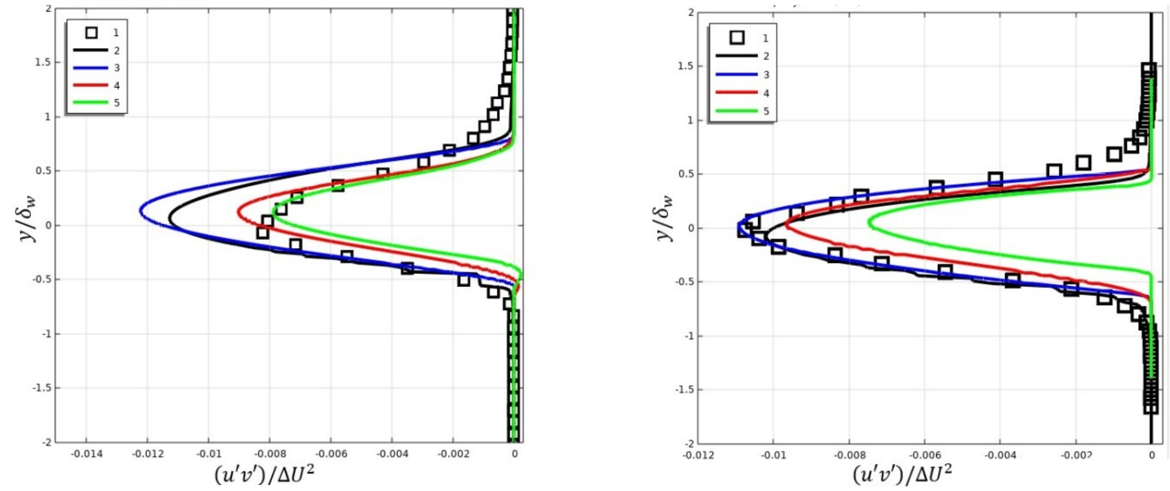


e)

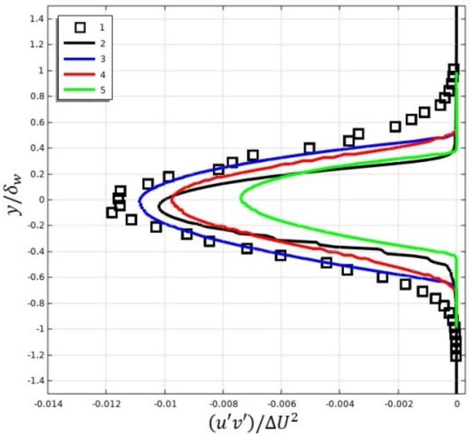
Fig. 11. Profiles of dimensionless longitudinal velocity at different sections of the channel. a) x=1 mm, b) x=50 mm, c) x=200 mm, e) x=650 mm, f) x=950 mm, 2-two-fluid model, 3-SST model, 4-SA model, 5-v2-f model.

The results in the x=1 mm section of all turbulence models describe the flow well. The velocity at x=50 mm lags significantly behind the experiment at the breaking point. In sections from x=200 mm up to 950 mm, the results of the two-fluid model and SST are better than the results obtained using other models.

Figure 12 shows the numerical results of the turbulence model and experiment for turbulent stress $\overline{u'\vartheta'}$ profiles at sections a) x=200 mm, b) 650 mm, c) 950 mm.



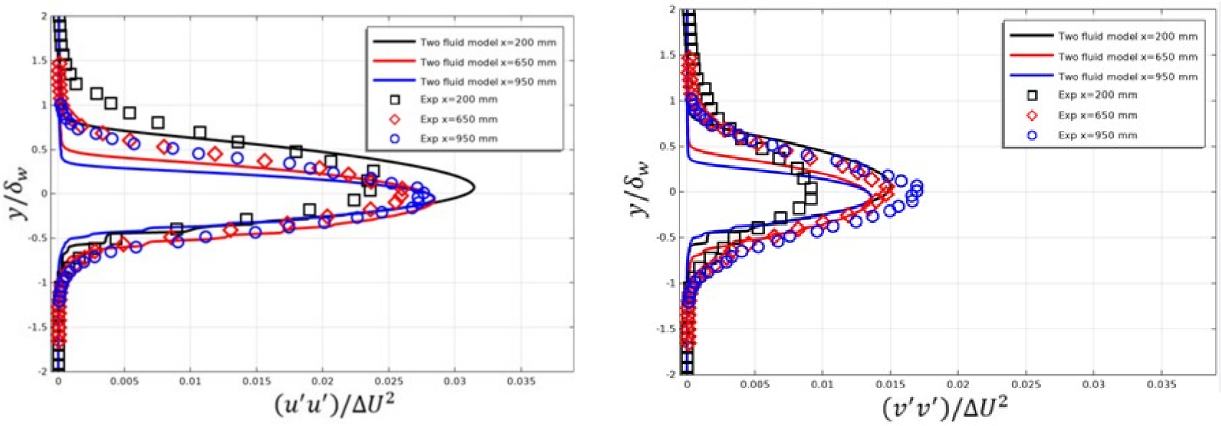
a) b)



c)

Fig. 12. Profiles of turbulent stresses $\overline{u'\vartheta'}$. a) x=200 mm, b) x=650 mm, c) x=950 mm, 1-experiment, 2-two-fluid model, 3-SST model, 4-SA model, 5-v2-f model.

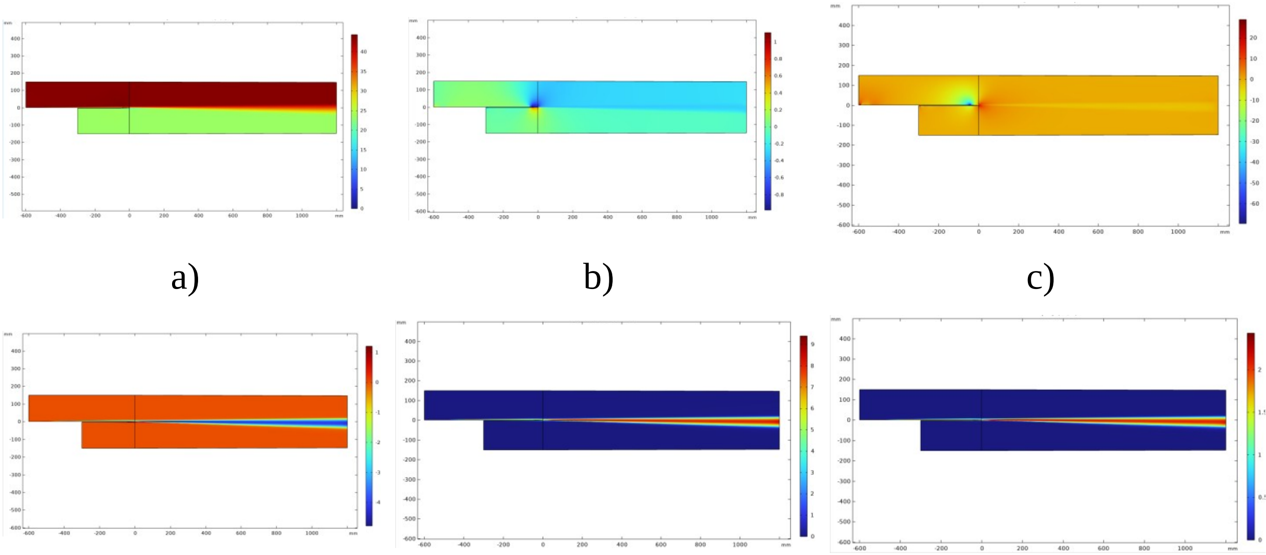
As can be seen from Fig. 12, the turbulent stresses $\overline{u'\vartheta'}$ in the section x=200 mm, the results of the SA and v2-f models are in good agreement with the experimental ones, and the results of the two-fluid model and SST are 1.5 times greater than the experiment. In other sections, the results of the models can be considered satisfactory. Figure 13 shows the results of the two-fluid model for turbulent stresses $\overline{u'u'}$ and $\overline{v'v'}$.



a) b)

Fig. 13. Profiles of turbulent stresses.

In Fig. 14, contours for the longitudinal velocity and turbulent stresses are presented for the two-fluid model.



a) b) c)

d) e) f)

Fig. 14. Isolines of a) longitudinal velocity –U, b) transverse velocity–V, c) pressure–p, turbulent stress d) $\overline{u'v'}$, e) $\overline{u'u'}$, f) $\overline{v'v'}$.

Results and Discussion

Laminar Flow Mixing: In laminar regimes, the mixing process is primarily governed by viscous diffusion, and the interface between the two flows remains smooth. The mixing efficiency can be modeled by solving the advection-diffusion equation. It was observed that the rate of mixing is slow and highly dependent on the velocity gradient at the interface. In this regime, shear stress plays a significant role in how quickly the two flows integrate.

Turbulent Flow Mixing: As the Reynolds number increases, instabilities arise, and the flow transitions to turbulence. In turbulent mixing, eddies and vortices form, enhancing the mixing process through chaotic advection. Large-scale coherent structures such as vortices tend to stretch and fold the flow, increasing the area of contact between the two streams and promoting faster homogenization. The Kolmogorov scale, representing the smallest eddies in turbulent flow, was crucial for understanding the efficiency of mixing in this regime.

Vortex Dynamics and Shear Flow: The generation of vortices and the behavior of shear layers were central to the study of flat flow mixing. The formation of Kelvin-Helmholtz instabilities in regions of high velocity gradient between the two flows significantly influenced the mixing rate. These instabilities developed into roll-up vortices, which increased the efficiency of the process. Vortex shedding from the boundaries of the flow also played an essential role in mixing enhancement.

Practical Implications: Understanding flat flow mixing is critical in applications such as pollutant dispersion in atmospheric boundary layers, mixing in microfluidic devices, and the design of heat exchangers. In environmental contexts, flat flow mixing models help predict the transport and diffusion of contaminants in water bodies and the atmosphere.

Conclusion

The mixing of two flat flows is a complex process influenced by various physical parameters such as Reynolds number, velocity gradients, and boundary conditions. In laminar flows, mixing is dominated by diffusion and occurs slowly. In contrast, turbulent flows feature enhanced mixing through chaotic advection and the presence of vortices. Vortex dynamics and shear instabilities are pivotal in promoting mixing in both laminar and turbulent regimes. By understanding these mechanisms, it is possible to design systems that optimize mixing efficiency for industrial, environmental, and engineering applications.

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