Particle deposition on the walls of a turbulent flow

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Abstract

Direct numerical simulations (DNS) have been performed to study particle deposition in a turbulent channel flow at a Reynolds number $Re_\tau = 150$ based on the half channel width and the wall shear velocity. The Pencil Code was used for generating the three-dimensional and time-dependent flow field in the channel.

Particles were implemented in the simulated channel flow after the turbulence was fully developed. The drag force was considered to be the only force acting on the particles. An ensemble of 100,000 particles was distributed close to the lower wall. There were preformed six simulations with six different particle sizes. The number of deposited particles was registered, and the particle deposition velocity was estimated each simulation.

The obtained numerical results were compared to the predictions of an empirical equation, earlier simulations and experimental data. A reasonable agreement was observed, even though the drag force was the only force considered in this work. It was noticed that the size of the particles influenced the deposition velocity.

Preface

Background for project

This project serves as the specialization project required to obtain the degree Master of Science in Applied Physics and Mathematics at the Norwegian University of Science and Technology (NTNU). The project was organized as a teamwork with two students working together and being evaluated on the same basis.

The project was carried out in the 9th semester of the degree under the supervision of Nils Erland L. Haugen from SINTEF Energy Research. SINTEF is Scandinavia's largest, independent research organization and is an important collaborator to many companies in Norway and abroad. Also, SINTEF has a close collaboration with NTNU, and every year they offer many different specialization projects to the students at NTNU.

The specialization project comprises a workload of 15 ECTS which corresponds to approximately 24 hours a week per student. The workload includes acquiring completing knowledge through literature studies, setting up project goals and implementing suggested solutions in addition to writing the final report.

This report documents the work done and the results obtained.

Chapter description

The report is organized into seven chapters.

Chapter 1: Introduction covers the background information on the subject of this project. Earlier works on the subject are discussed, and a brief introduction to the overall objectives is given.

Chapter 2: Numerical methods describes the numerical methods that are used to solve the equations of motion for the fluid. The ideas behind the Pencil Code are introduced.

Chapter 3: Turbulent flows gives a description of turbulent flows. Characteristics features and are presented and explained. Turbulent duct flow is also explained.

Chapter 4: Particles in flows presents the equations of the particle motion. The different forces acting on a particle in a turbulent flow are presented. Formalisms of particle deposition are introduced.

Chapter 5: Computer simulations describes the turbulent channel flow used as initial conditions for the simulations with particles. The physical properties, computational domain and boundary conditions of the channel are given. The statistics of the turbulent flow obtained are discussed.

Chapter 6: Results presents the results of the simulations with particles in a channel flow.

Chapter 7: Discussion and conclusion consists of a discussion of the results before a conclusion is presented. Possible further work is also discussed.

Following the last chapter a list of notations used in this report is given, as well as a bibliography.

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Chapter 1

Introduction

Particle deposition on walls is a problem in many applications such as combustion chambers of municipal solid waste incinerators, the interior of computers or the inside of ventilation systems. To handle and minimize this deposition it is necessary to acquire detailed knowledge about turbulent channel flows and the mechanisms for particle deposition.

Before one can start to investigate the different mechanisms for particle deposition, it is necessary to acquire basic knowledge of turbulent flows. Chapter 2 presents the fluid flow equations and the numerical methods needed to acquire solutions from these equations. In chapter 3 the physical properties of turbulent flows are presented.

In the 19th century the Irish mathematician George S. Stokes and the French engineer Claude Navier independently found that all flow of fluids are governed by a partial differential equation later named the Navier-Stokes equation [White, 2005]. This equation is seemingly quite simple, but it has solutions that are not fully understood even to this day. The Navier-Stokes equation express conservation of momentum for a flow and is a very important equation in fluid dynamics.

Osborne Reynolds did a number of experiments with pipe flows in the late eighteen hundreds where he studied the transition between laminar and turbulent flows. A dimensionless parameter which correlates the viscous behavior of fluids was later named after him [White, 2005]. The Reynolds number is an important property of the flow and not the fluid. Low Reynolds number indicates a viscous, smoothly varying, laminar flow whereas high Reynolds number implies a turbulent flow with fast-varying velocity fluctuations in all three dimensions.

A turbulent flow consists of a large range of scales, both length scales and time scales. In the nineteen hundreds, Andrey Kolmogorov introduced his ideas of the smallest scales in a turbulent flow. In his *universal equilibrium theory* he argued that the smallest scales in a flow are statistically independent of the large scales, i.e. the large-scale turbulence and the mean flow, so that the smallest scales are similar for every turbulent flow [Tennekes and Lumley, 1983]. He found that the smallest length scale, velocity scale and time scale were all functions of the dissipation rate and the viscosity. The dissipation, i.e the process where energy is converted into heat, is due to the viscous forces in the flow. The viscous forces destroys the smallest eddies and converts their kinetic energy into thermal energy.

Turbulence can occur in all fluids as long as the flow velocity is sufficiently high. The state of turbulence is unsteady, three-dimensional and extremely complex. However, all the characteristics of turbulent flows are embodied in the Navier-Stokes equations for fluid motions. For turbulent flows the solutions to these equations are complex and must be found numerically. This has just been possible since the 1980s after the many advances in computer science. Directly solving the Navier-Stokes equations with numerical methods is called direct numerical simulations (DNS) and today the data produced by DNS is considered as valid as data from experiments. DNS use no models or approximations to solve the Navier-Stokes equations, i.e. the whole range of spatial and temporal scales in the turbulence is resolved. This puts requirements on the computational mesh which results in calculations demanding many CPU hours. In engineering it is therefore usual to make use of turbulence models to keep the computational costs at a minimum. These computational methods are Reynolds-averaged Navier-Stokes (RANS) and large eddy simulation (LES). The numerical methods are further discussed in chapter 2.

The first DNS of a plane channel flow was performed by Kim et al (1987). The data from this successful simulation is still used as comparison for accomplished simulation data to see if the simulation produces a realistic flow.

In this work DNS was used to solve the Navier-Stokes equations for a turbulent channel flow. The simulation code used was the Pencil Code which is further discussed in chapter 2.3. The Pencil Code was initiated by Axel Brandenburg and Wolfgang Dobler to study different types of astrophysical flows.

The concept of transport and deposition of particles in a fluid flow has been studied experimentally for a long time and many theories have been developed based on the experimental data produced. The theory behind particle motions in fluid is discussed in chapter 4. In 1984 Papavergos and Hedley collected experimental data from earlier work and compared the different theories that had been developed regarding particle deposition in turbulent flows. In 1989 McLaughlin performed the first DNS simulation with particles in a turbulent channel flow and in 1993 Fan and Ahmadi developed the empirical model for the particle deposition velocity that is used as comparison for the DNS data produced in this report. In 2000 Zhang and Ahmadi did an investigation on the effect of gravity on particle transport and deposition in a turbulent channel flow.

In this work the Pencil Code was used to implement particles into the turbulent channel flow. The drag force was assumed to be the only force acting on the particles. The particle location and time were registered if the particle deposited on one of the walls of the channel. The particle was removed from the simulation after deposition. The deposition velocity was estimated for different particle sizes and compared with earlier work. The results from this work are presented in chapter 6.

Nomenclature

c	Speed of sound	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
C_c	Stokes-Cunningham slip correction factor	[1]
D	Brownian diffusivity	$\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$
d	Particle diameter	[m]
d^+	Non-dimensional particle diameter	[1]
ϵ	Dissipation rate	$\left[\frac{\mathrm{m}^2}{\mathrm{s}^3}\right]$
η	Kolmogorov length	[m]
$\mathbf{F}_B^+$	Non-dimensional Brownian force	[1]
$\mathbf{F}_D^+$	Non-dimensional drag force	[1]
$\mathbf{F}_g^+$	Non-dimensional gravitational force	[1]
$\mathbf{F}_L^+$	Non-dimensional lift force	[1]
g^+	Non-dimensional gravity	[1]
k^+	Non-dimensional surface roughness	[1]
k_B	Boltzmann's constant	$\left[\frac{\mathrm{J}}{\mathrm{K}}\right]$
L_i	Length of spatial directions in the channel	[m]

L_1^+	Saffman's lift force coefficient	[1]
λ	Mean free path of molecules in fluid	[m]
M	Mach number	[1]
m_p	Particle mass	[kg]
μ	Viscosity	$\left[\frac{\mathrm{kg}}{\mathrm{s\cdot m}}\right]$
N_0	Initial number of particles	[#]
N_d	Number of deposited particles in time duration t_d^+	[#]
ν	Kinematic viscosity	$\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$
P	Pressure	[Pa]
R_{ii}	Two-point correlation function	[1]
Re	Reynolds number	[1]
Re_c	Reynolds number based on center velocity	[1]
Re_p	Particle Reynolds number	[1]
Re_τ	Reynolds number based on wall shear velocity	[1]
ρ_f	Density of the fluid	$\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$
ρ_p	Density of the particles	$\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$
S	Particle-to-fluid density ratio	[1]
S_c	Schmidt number	[1]

T	Temperature	[K]
t_d+	Time duration of number of deposited particles N_d	[1]
τ_p^+	Non-dimensional particle relaxation time	[1]
$\mathbf{U}$	Instantaneous fluid velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
$\mathbf{u}$	Fluid mean velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
$\mathbf{u}$	Fluid velocity fluctuation	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
u^+	Non-dimensional fluid velocity fluctuation	[1]
U_c	Centerline velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
u_d^+	Non-dimensional particle deposition velocity	[1]
$\mathbf{u}_{\mathrm{rms}}$	Root-mean-square fluid velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]$
u_τ	Wall shear velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]$
$\mathbf{V}$	Particle velocity	$\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]$
ω	Vorticity	$\left[\frac{1}{\mathrm{s}}\right]$
s^+	Non-dimensional distance from the walls	[1]
s_0^+	Distance from the wall where particles are distributed	[1]

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