Simulation of turbulent particle deposition in rough pipes using an Euler-Lagrange approach

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Abstract

Numerical investigations of solid particle deposition in turbulent particle-laden flow have been carried out by using an Euler-Lagrange approach. The cyclic large-eddy simulations of five different geometries of multiple-started helically rib-roughened pipes have been performed for a Reynolds number of $Re = 16000$. The impact of the pipe geometry on the particle deposition is shown by comparing the simulation results of the deposition velocity u_{d}^{+} for different particle relaxation times τ_{p}^{+} and geometric parameters. Simulation pressure results are used to further assess the pipe geometries in terms of pressure loss.

1 Introduction

Accumulations of solid particles lead to an additional thermal resistance in heat exchanger pipes and reduce the heat transfer [1]. Especially in rough pipes, deposits have a significant effect due to structural changes of the inner surface [2]. However, internally rib-roughened pipes are usually developed with regard to heat transfer and pressure loss and not with regard to particulate deposition.

The deposition of solid material is strongly dependent on the geometric parameters of a pipe (cf. fig.1) and the operating conditions. Further, the process of particulate deposition usually occurs over several operating hours or days. Those are reasons, why former investigations have been mostly done experimentally by long-term measurements [3]. Growing computational resources allow using numerical simulations to investigate particle transport, as done in Kasper et al. [4]. Nevertheless, detailed simulations of the turbulent flow in rough pipes can only be performed for a few seconds of physical time. Therefore, a certain numerical approach is necessary to make predictions about solid deposition in such pipes.

In the present research, multiphase large-eddy simulations (LES) of turbulent pipe flows are performed by using an Euler-Lagrange approach. Deposition rates and velocities as functions of the particle relaxation time are determined for multiple-started helically rib-roughened pipes with different rib heights e, number of starts n_{s}, helical rib angles α, and contact angles β. The goal of the investigations is to analyze the impact of geometrical parameters on the deposition rate. The results of such numerical calculations can be used to support the development process of new pipes with regard to the deposition of particles.

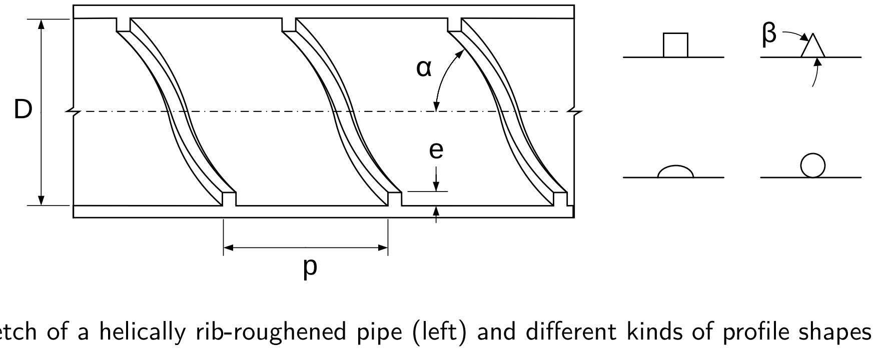

Figure 1: Sketch of a helically rib-roughened pipe (left) and different kinds of profile shapes (right) cf. [5]

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2 Numerical approach

The LES are performed in the open-source CFD (computational fluid dynamics) library OpenFOAM® (open source field operation and manipulation). The physical modelling of the numerical calculations is based on the conservation equations of continuity and momentum [6]. For the subgrid scale modelling the WALE [7] turbulence model is used. A Lagrange approach is used for the spherical particles and the particle motions are calculated with Newton's laws of motion [8].

A computational domain of $L = x \cdot D$ with periodic (cyclic) boundary conditions in streamwise direction is used in order to get a fully developed turbulent flow. In figure 2 a schematic representation of the domain is shown. Periodic boundary conditions are applied to the continuous as well as the dispersed phase. To maintain a constant average velocity U_m, a source term is added to the momentum equation and to maintain a constant particle to fluid volume ratio, the number of stuck particles is re-injected to the flow.

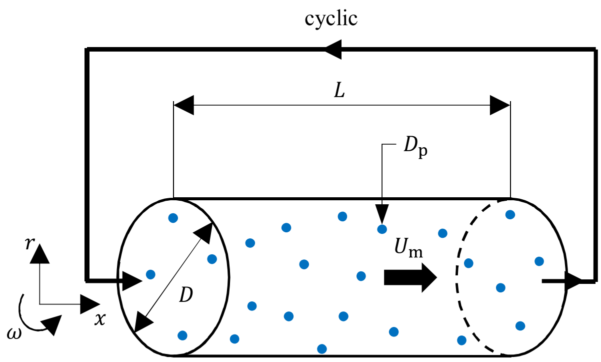


Figure 2: Schematic representation of the computational domain

The one-way coupled particle-laden LES run for a sufficiently long time to be in a quasi steady-state. Then, the constant deposition rates are evaluated and the deposition velocities are determined by

$$u_\mathrm{d} = \frac{\dot{N}_\mathrm{d}/A}{N_\mathrm{p}/V} \tag{1}$$

where $\dot{N}_\mathrm{d}$ is the deposition rate, N_p is the constant number of particles in the flow, V is the domain volume, and A is the adhesive surface. The dimensionless form can be determined by $u_\mathrm{d}^+ = u_\mathrm{d}/\bar{u}_\tau$ where $\bar{u}_\tau$ is the mean friction velocity.

3 Simulation configurations

The number of particles is kept constantly at 600×10^3 and the density ratio between the dispersed and continuous phase is $S = \dot{m}_\mathrm{p}/\dot{m}_\mathrm{c} = 2.5$, where $\dot{m}_\mathrm{p}$ and $\dot{m}_\mathrm{c}$ are the mass flow rates of the dispersed and the continuous phase, respectively. Gravitation is neglected and the Reynolds number is $Re = 16000$. The number of cells of the meshes is between 12×10^6 and 14×10^6, which result in $y^+ \leq 1$ for all simulations. Further, the particle diameters are in the range of $8\,\mu\mathrm{m} \leq D_\mathrm{p} \leq 50\,\mu\mathrm{m}$. Since in the current research no interactions of the particles with the continuous phase or turbulence and dissipations enhancements shall be investigated, only one-way coupling is considered.

Simulations were performed in a domain of the length of $L = 2D$ and the rib height e and the number of starts n_s were varied in order to investigate their impact on the deposition rate. When changing the rib height e, the contact angle β automatically changes if the pitch length of the roughness elements p remains the same. Same is true for the number of starts n_s and the helical rib angle α. Therefore, the contact angle β and the helical rib angle α also change for a specific combination of geometry parameters.

4 Results and discussion

Each LES was performed parallel on 168 cores and ran for three days, which results in ≈ 12000 cpu-hours per run. Within these three days, a length of about 32 passed pipe diameters has been simulated. After about $L = 20D$ the deposition rate becomes constant, as can be seen in figure 3 a) where the deposited particles for three different diameters is shown.

In table 1 the pressure loss results $\Delta p/L$ of all investigated pipe geometries are summarized. It can be noticed that the highest pressure loss occurs for the highest helical angle $\alpha = 72°$ and the lowest number of starts $n_\mathrm{s} = 6$. Further, an increase of the ratio p/e, as well as the contact angle β, leads to higher pressure losses. Moreover, the mean friction velocities $\bar{u}_\tau$ of the five geometry variants are listed in the table below.

Table 1: Results of the pressure loss per length $\Delta p/L$ for the different pipe geometries, $Re = 16000$

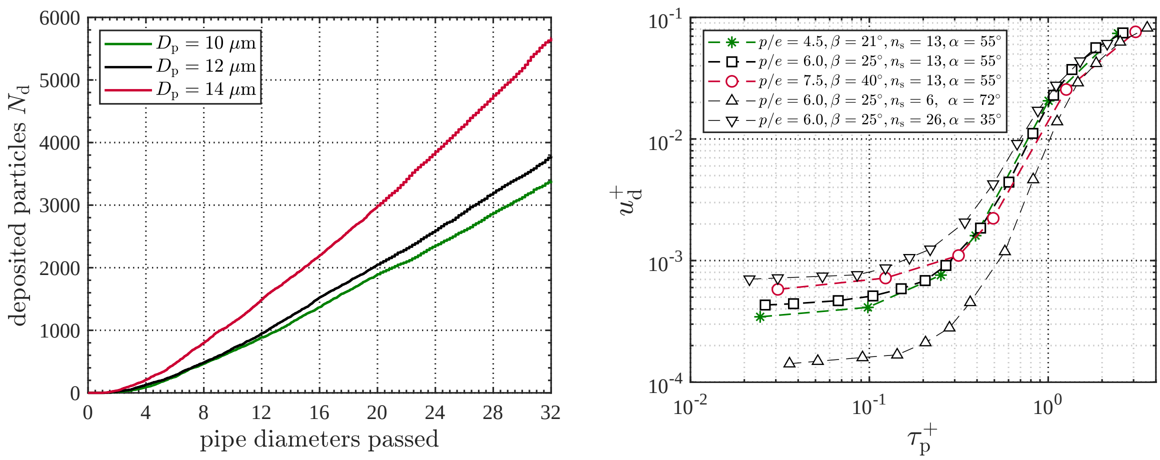
p/e	β	n_s	α	$\Delta p/L$	$\bar{u}_\tau$
4.5	21°	13	55°	≈ 1762 Pa/m	0.094
6	25°	13	55°	≈ 1880 Pa/m	0.087
7.5	40°	13	55°	≈ 2217 Pa/m	0.084
6	25°	6	72°	≈ 2570 Pa/m	0.1
6	25°	26	35°	≈ 1535 Pa/m	0.078

The constant deposition rate $\dot{N}_\mathrm{d}$ after ten through flows has been used to determine the deposition velocity according to eqn. 1. In figure 3 b) the results of dimensionless deposition velocity u_d^+ as a function of the dimensionless particle relaxation time τ_p^+ are depicted. The dimensionless form of the particle relaxation time can be determined by

$$\tau_\mathrm{p}^+ = \frac{C D_\mathrm{p}^2 \bar{u}_\tau^2}{18 \nu_\mathrm{c}^2} \cdot S \tag{2}$$

where C is the Cunningham slip correction factor and ν_c is the kinematic viscosity of the fluid.

Note in figure 3 b) that for higher p/e ratios and higher contact angles β the deposition velocity is increased for $\tau_\mathrm{d}^+ \leq 0.3$. For $\tau_\mathrm{d}^+ \geq 0.3$ the impact of the ratio p/e and the angle β has a minor effect on the deposition velocity.



a) Deposited particles N_d for different particle diameters during several through-flows, $p/e = 6$ and $n_\mathrm{s} = 13$

b) Dimensionless deposition velocity u_d^+ as a function of the relaxation time τ_p^+ for different pipe geometries

Figure 3: Simulation results for different particle diameters and pipe geometries

A decrease of the number of starts n_s, which results in a increase of the helical rib angle α, leads to smaller deposition velocity values for $\tau_\mathrm{d}^+ \leq 3$. For more number of starts, higher deposition velocities can be noticed. Furthermore, at a particle relaxation time $\tau_\mathrm{p}^+ \geq 3$ the deposition velocity approach a value of $u_\mathrm{p}^+ \approx 0.1$ for all geometries. Such a behavior can also be seen in Fan and Ahmadi [9] who determined deposition velocities in duct flow simulations with different roughness.

5 Conclusion and outlook

Several multiphase simulations with different pipe geometries and particle diameters have been performed. Deposition velocities have been determined and the impact of different geometric parameters on particle deposition is shown graphically. The results can be used to assess the geometry of multiple-started rib-roughened pipes in terms to solid deposit. Furthermore, an adhesion and removal model can be added to the simulation to take into account physical effects like rebound and re-entrainment of stuck particles in future simulations. In addition, heat transfer simulations can be performed in order to evaluate multiple-started helically rib-roughened pipes in terms of pressure loss, heat transfer, and solid deposition.

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References

[1] T.R. Bott. General fouling problems. In: L.F. Melo, T.R. Bott, C.A. Bernardo. (eds) Fouling science technology. Springer, Dodrecht vol. 145 (1988)

[2] R.L. Webb, N.H. Kim. Principles of enhanced heat transfer. Taylor and Francis Group, 2nd edition (2005)

[3] H. Müller-Steinhagen, F. Reif, N. Epstein, and A.P. Watkinson. Influence of operating conditions on particulate fouling. Canadian J. of Chem. Eng. 66 (1988) 42–50.

[4] R. Kasper, J. Turnow, and N. Kornev. Numerical modeling and simulation of particulate fouling of structured heat transfer surfaces using a multiphase Euler-Lagrange approach. Int. J. of Heat and Mass Transf. 115 (2017) 932–945

[5] D.L. Gee, R.L. Webb. Forced convection heat transfer in helically rib-roughened tubes. Int. J. Heat and Mass Transfer 23 (1980) 1127–1135.

[6] J. Anderson. Computational Fluid Dynamic. McGraw-Hill. Inc.: New York, USA. (1995)

[7] F. Nicoud, F. Ducros. Subgrid-scale stress modelling based on the square of the velocity gradient tensor. Flow. Turb. and Comb. 62 (1999) 183–200.

[8] M. Sommerfeld. VDI Heat-Atlas. Particle motion in fluids. Springer-Verlag, Berlin, Heidelberg. (2010)

[9] F. Fan, G. Ahmadi. A sublayer model for turbulent deposition of particles in vertical ducts with smooth and rough surfaces. J. Aerosol Sci. 24(1) (1993) 45–64