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Large eddy simulations of a buoyant plume above a heated horizontal cylinder at intermediate Rayleigh numbers

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ABSTRACT

Large eddy simulations of a buoyant plume forming above a heated horizontal cylinder with a Rayleigh number of 9.4E7 is carried out and compared with experimental data. Natural convection heat transfer from a horizontal cylinder at this intermediate Rayleigh number involve a laminar to turbulent transition downstream the cylinder. A laminar to turbulent transition will alter the flow characteristic downstream cylinder considerably, thus it is important that the transition is captured in the simulations. Subgrid stresses are accounted for using the dynamic Smagorinsky model which allow for both laminar and turbulent flow through the dynamic procedure.

The results show a considerable difference between the numerical and experimental results. Plume center vertical velocity is highly overpredicted compared to the experimental data. The computed half-width about 1.5 y/D downstream the cylinder is comparable to the experimental data, however, 3.5 y/D downstream cylinder, the half-width is only about half that of the experimental data. The half-width growth rate measured in the experiments remain higher than the computed growth rate throughout the domain of interest.

1. Introduction

Natural convection heat transfer from horizontal cylinders have been under scrutiny for about a century, see e.g. Grafsrønningen et al. [2] for a brief summary of the earliest papers. Research on natural convection heat transfer from horizontal cylinders has resurfaced a number of times since the first theoretical and experimental investigations with the introduction of new experimental, analytical or numerical techniques, and a vast number of articles have been published within the topic. Natural convection heat transfer from horizontal cylinders has a fundamental significance in design of heat exchangers, pipelines, HVAC-systems and other applications. In buoyant flows the Nusselt number Nu, Rayleigh number Ra, Grashof number Gr and Prandtl Pr number play vital roles. The Nusselt number is a measure of the ratio between convective to conductive heat transfer from solids to fluids, whereas the Rayleigh number is the product of the Grashof number and Prandtl number $Ra = GrPr$. The Grashof number is the ratio of buoyant forces and viscous forces and the Prandtl number Pr is kinematic viscosity over thermal diffusivity. A number of empirical correlations which relates the Nusselt number to the Rayleigh number exists, cf. Morgan [3] or Kitamura et al. [4]. However, in design of complex heat exchangers based solely on natural convection heat transfer, empirical correlations for a single unbounded horizontal cylinder under quiescent conditions are not sufficient. The correlations would not yield satisfactory results, cf. e.g. Gyles et al. [5].

Computational Fluid Dynamics (CFD) is widely used in design of heat exchangers. CFD is an excellent tool, when used correctly, which may provide results for complex geometries in a fraction of the time it takes to build an experimental setup and at significantly reduced cost. When used together and verified against experiments, CFD may provide knowledge about unmeasurable quantities, or yield results about small scale features which hardly are measurable.

Design of subsea heat exchangers based solely upon natural convection heat transfer, with the aid of CFD tools, is not straightforward. Natural convection flow associated with full scale heat exchangers for the energy sector are often turbulent, or undergoing a laminar to turbulent transition. The CFD tools must therefore be able to predict the onset of transition from laminar to turbulent flow accurately without any knowledge of the route to turbulent

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Nomenclature

C_p	Specific heat capacity – (J/kgK)
D	Cylinder diameter – (m)
Gr	Grashof number – $\frac{g\beta(T_w - T_\infty)D^3}{\nu^2}$ (–)
$Gr_{Q,Y}$	Local Grashof number $\frac{g\beta Qy^3}{\rho C_p \nu^3}$ (–)
Nu	Nusselt number – $\frac{hD}{k}$ (–)
P	Pressure – (Pa)
Pr	Prandtl number – $\frac{\nu}{\alpha}$ (–)
Q	Heat per length –(W/m)
R	Cylinder radius – (m)
Ra	Rayleigh number – $\frac{g\beta(T_w - T_\infty)D^3}{\alpha\nu}$ (–)
T	Temperature – (K)
U	Horizontal velocity – (m/s)
V	Vertical velocity – (m/s)
W	Spanwise velocity – (m/s)
g	Gravity – (m/s^2)
k	Thermal conductivity – (W/mK)
t	Temperature fluctuation – (K)
u	Horizontal velocity fluctuation – (m/s)
v	Vertical velocity fluctuation – (m/s)
w	Spanwise velocity fluctuation – (m/s)
x	Cartesian coordinate, horizontal distance from cylinder center – (m)
y	Cartesian coordinate, vertical distance above cylinder center – (m)

Greek

α	Thermal diffusivity – $\frac{k}{\rho C_p}$ (m^2/s)
β	Coefficient of thermal expansion – (1/K)
η	Length scale – (m)
μ	Molecular viscosity – (kg/ms)
ν	Kinematic viscosity – (m^2/s)
ρ	Density – (kg/m^3)
θ	Circumferential angle – (°)
ϑ	Dimensionless coordinate – $\frac{x}{y-B}$ (–)

Subscripts

∞	Ambient condition
B	Batchelor
f	Film condition evaluated at $(T_w + T_\infty)/2$
Inf.	Inflection point
w	Wall condition

Superscripts

–	Ensemble average
~	Filtered quantity

flow nor tuning of turbulence models. This is most likely the single most important physical feature the simulation must capture which makes heat transfer predictions especially challenging.

Subsea heat exchangers are vital parts of subsea gas boosting modules and other subsea processing modules. A subsea heat exchanger may consist of multiple connected horizontal cylinders forming meandering tubes, see Gyles et al. [5] for an example. Grafsrønningen et al. [2] and Grafsrønningen and Jensen [1] investigated the buoyant plume forming above a single heated horizontal cylinder in a quiescent environment. The results showed that the plume transitioned from laminar to turbulent flow a distance downstream the cylinder.

Pham et al. [6] pointed out that pure thermal plumes are examples of very complex flows due to quick unstable growth resulting in abrupt transition from laminar to turbulent flow. Thus despite its very simple geometry, the buoyant plume forming above a single cylinder involves a troublesome laminar to turbulent transition, hence simulations of a single heated horizontal cylinder and comparison with experimental results may provide valuable feedback on the performance of CFD-tools for such applications. A transition will influence the transport and mixing properties downstream the cylinder significantly and possibly influence the efficiency and design of large heat exchangers to a great extent. It is therefore important that the transition is captured in the simulations.

Contradictory to pipe flow, where large perturbations are required to trigger turbulent flow, linear stability theory show that buoyant plumes are unstable to infinitesimal perturbations, thus a reproducible transition onset should be obtainable in numerical simulations, cf. Eckhardt [7] and Gebhart et al. [8]. Downstream a critical location, which is available from linear stability theory and some critical local Grashof number, the flow is unstable to ever-present minute disturbances.

Natural convection heat transfer from heated horizontal cylinders has been investigated by a number of researchers. Kuehn and Goldstein [9] studied laminar natural convection heat transfer from a horizontal cylinder numerically for Rayleigh number ranging from 1 to $1E7$. Farouk and Güçeri [10] investigated laminar natural convection heat transfer from a horizontal cylinder using a finite difference technique. Merkin and Pop [11] examined natural convection heat transfer around and above a cylinder by solving a set of boundary layer equations. Saitoh et al. [12] presented results from numerical simulations of laminar natural convection flow around a heated horizontal cylinder as a benchmark solution for various Rayleigh and Prandtl numbers. Yüncü and Batta [13] investigated laminar natural convection heat transfer from a single and two vertically arranged horizontal cylinders using a finite difference technique. Recently Demir [14] investigated laminar natural convection heat transfer from a concrete cylinder numerically.

The articles mentioned hitherto were all of laminar natural convection heat transfer, i.e. turbulent effects were either not present or neglected. Even though the Rayleigh number based on the cylinder diameter implies laminar flow, the plume often undergoes a transition to turbulent flow downstream the cylinder. Noto et al. [15] investigated the buoyant plume forming above a horizontal wire in air. The Rayleigh number based on wire diameter was in the order of unity, yet the plume underwent a transition from laminar to turbulent flow downstream the cylinder. Noto et al. [15] presented a transition criteria for planar buoyant plumes above cylinders or wires based on the local Grashof number $Gr_{Q,Y} = \frac{g\beta QY^3}{\rho C_p \nu^2}$. If $Gr_{Q,Y}$ is less than $2E8$ the flow is laminar, if $2E8 < Gr_{Q,Y} < 2E9$ the flow is transitional, and for $Gr_{Q,Y} > 2E9$ the flow is turbulent. Hence, turbulent effects cannot be neglected in plumes, particularly not downstream the cylinder were accurate predictions of the flow and temperature fields are required. The criterion proposed by Noto et al. [15] was compared with the experimental results by Grafsrønningen et al. [2] and Grafsrønningen and Jensen [1] and showed a relatively good fit.

Farouk and Güçeri [16] used a $k-\varepsilon$ model to account for turbulent effects and computed the natural convective flow around a cylinder at Rayleigh numbers ranging from $Ra = 5E7$ to $1E10$.