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Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations

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ABSTRACT

Urban physics is the science and engineering of physical processes in urban areas. It basically refers to the transfer of heat and mass in the outdoor and indoor urban environment, and its interaction with humans, fauna, flora and materials. Urban physics is a rapidly increasing focus area as it is key to understanding and addressing the grand societal challenges climate change, energy, health, security, transport and aging. The main assessment tools in urban physics are field measurements, full-scale and reduced-scale laboratory measurements and numerical simulation methods including Computational Fluid Dynamics (CFD). In the past 50 years, CFD has undergone a successful transition from an emerging field into an increasingly established field in urban physics research, practice and design. This review and position paper consists of two parts. In the first part, the importance of urban physics related to the grand societal challenges is described, after which the spatial and temporal scales in urban physics and the associated model categories are outlined. In the second part, based on a brief theoretical background, some views on CFD are provided. Possibilities and limitations are discussed, and in particular, ten tips and tricks towards accurate and reliable CFD simulations are presented. These tips and tricks are certainly not intended to be complete, rather they are intended to complement existing CFD best practice guidelines on ten particular aspects. Finally, an outlook to the future of CFD for urban physics is given.

1. Introduction

> "Scientists study the world as it is; engineers create the world that has never been."[1]

Urban physics is the science and engineering of physical processes in urban areas. It basically refers to the transfer of heat and mass in the outdoor and indoor urban environment, but also their interaction with humans, fauna, flora and materials. From the human point of view, the main aim of urban physics is to provide a healthy, comfortable and sustainable outdoor and indoor built environment taking into account climatic, energetic and economic constraints. As such it is strongly related to the grand societal challenges climate (change), energy, health (including comfort), security, transport and aging.

In urban physics, science and engineering are strongly intertwined. Urban physics is an applied discipline. It is also inherently multidisciplinary. In its narrowest sense, it has its roots in building engineering/building physics, civil engineering and architectural engineering, and it is strongly based on mathematics, physics and chemistry. However, urban physics is a rapidly expanding discipline. The main reasons are the increasing urbanization and the fact that urban physics is key to understanding and addressing the grand societal challenges pertaining to this increasing urbanization. Because of the increasing importance of urban physics, the past decades have seen a tremendous growth of the urban physics community. Scientists and engineers from disciplines that traditionally did not have an explicit focus or even no focus at all on buildings and urban areas, are now shifting the focus of the work in

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[1] Theodore von Kármán (1881–1963), Hungarian-American mathematician, physicist and aerospace engineer.

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their discipline to buildings and urban areas. As a result, in this broader sense, urban physics is practiced in many more engineering disciplines, from mechanical and electrical engineering over computer engineering and chemical engineering to urban planning and design, and it also draws from disciplines such as meteorology, human thermophysiology, psychology and material science.

Urban physics encompasses processes acting at a wide range of spatial and temporal scales, which will be addressed further in section 3 of this paper. The spatial scales that are the main focus in urban physics are the (meteorological) microscale and the building scale, where the former is defined as the scale of atmospheric motions with Lagrangian Rossby numbers greater than 200 or spatial scales of 2 km or less [1]. At these scales, many problems in urban physics can be tackled by one of three approaches, or a combination of these: (1) field measurements, (2) full-scale or reduced-scale wind-tunnel measurements; and (3) numerical simulation. In terms of numerical simulation, especially at the meteorological microscale, the main approach is Computational Fluid Dynamics (CFD).

Deciding which approach is most appropriate for a given problem is not always straightforward, as each approach has specific advantages and disadvantages. The main advantage of field measurements is that they are able to capture the real complexity of the problem under study. Important disadvantages however are that they are not fully controllable due to – among others – the inherently variable meteorological conditions, that they are not possible in the design stage of a building or urban area and that usually only point measurements are performed. The main advantages of wind-tunnel measurements are the large degree of control over the boundary conditions and test conditions and the fact that buildings, urban areas and their components can be evaluated in the design stage. However, as in field measurements, also in wind-tunnel measurements, generally only point measurements are performed. Techniques such as Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF) in principle allow planar or even full 3D data to be obtained, but the cost is considerably higher and application for complicated geometries can be hampered by laser-light shielding by the obstructions constituting the model, e.g. in case of an urban model consisting of many buildings. Another potential disadvantage of wind-tunnel testing is the required adherence to similarity criteria when testing at reduced scale. This can be a problem for, e.g., multiphase flow problems and buoyant flows. Examples are the transport and deposition of sand, dust, rain, hail, and snow, and buoyancy-driven natural ventilation and pollutant dispersion studies.

Numerical modeling with CFD can be a powerful alternative because it can avoid some of these limitations. It can provide detailed information on the relevant flow variables in the whole calculation domain ("whole-flow field data"), under well-controlled conditions and without similarity constraints. However, the accuracy of CFD is an important matter of concern. Care is required in the geometrical implementation of the model, in grid generation, in selection of proper solution strategies and in interpretation of the results. Selecting proper solution strategies includes choices between the steady Reynolds-averaged Navier–Stokes (RANS) approach, the unsteady RANS (URANS) approach, Large Eddy Simulation (LES) or hybrid URANS/LES, choices between different turbulence models, discretization schemes, etc. In addition, numerical and physical modeling errors need to be assessed by solution verification and validation studies. CFD validation in turn requires high-quality experimental data to be compared with the simulation results.

This paper focuses on CFD for urban physics. It consists of two parts. In the first part, the importance of urban physics related to the grand societal challenges is described (section 2), after which the spatial and temporal scales in urban physics and the associated model categories are outlined (section 3). In the second part, based on a brief theoretical

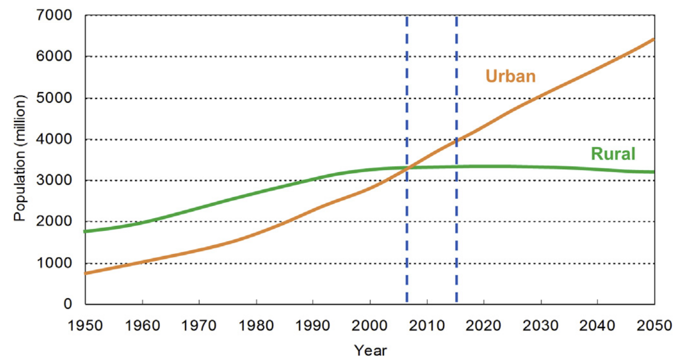

Fig. 1. Urban and rural population of the world, 1950–2050 (modified from Ref. [2]).

background, some views on CFD are provided. Possibilities and limitations are described (section 4), and in particular, ten tips and tricks towards accurate and reliable CFD simulations are presented (section 5). These tips and tricks are certainly not intended to be complete, rather they are intended to complement existing CFD best practice guidelines on ten particular aspects. Finally, an outlook to the future of CFD for urban physics is given (section 6).

2. Importance: grand societal challenges and application areas

> "One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike – and yet it is the most precious thing we have."[2]

2.1. Grand societal challenges

2.1.1. Urbanization

The grand societal challenges include climate, energy, health, security, transport and aging, many of which are interrelated and all of which are increasingly present in urban areas due to the continuing urbanization in the past decades. Urbanization is defined as a shift of the population from rural areas to urban areas. The 2014 Revision of World Urbanization Prospects by the United Nations (UN) mentions that currently and globally, more people live in urban areas than in rural areas [2]. While in 1950 only 30% of the world's population was urban, in 2014, this number has risen to 54%, and it is expected to reach 66% by 2050 [2] (Fig. 1). All regions are expected to urbanize further over the coming decades [2]. The UN state that urbanization is a major concern as this trend is "*changing the landscape of human settlement, with significant implications for living conditions, the environment and development in different parts of the world*" [3]. Indeed, while urbanization is generally associated with and driven by advantages such as improved opportunities, services and reduced costs for education, health, work, transport and housing, mainly resulting from centralization, it also entails considerable problems and challenges in terms of climate, energy, health, security, transport/mobility and aging, some of which are further explained below. The remainder of this section is not intended to be complete: the focus is on some main aspects of these challenges related to urban physics.

2.1.2. Climate change

In its Fifth Assessment Report, the International Panel for Climate Change (IPCC) states that human influence on the climate

[2] Albert Einstein (1879–1955), German theoretical physicist.