Building and Environment 96 (2016) 12–21

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

10 Questions

Ten questions concerning hybrid computational/physical model simulation of wind flow in the built environment

Robert N. Meroney

Colorado State University, Fort Collins, CO, USA

ARTICLE INFO

Article history:
Received 17 September 2015
Received in revised form
3 November 2015
Accepted 4 November 2015
Available online 21 November 2015

Keywords:
Hybrid research
Computational fluid dynamics (CFD)
Physical modeling
Experimental flow dynamics (EFD)
Built environment
Similitude

ABSTRACT

For over fifty years the common presumption has been that computational fluid dynamics (CFD) and experimental fluid dynamics (EFD) were mutually exclusive and competitive. Often the question was posed: *When can we get rid of our physical modeling facilities?* This question does not recognize the tremendous synergistic leverage of combining the best qualities of both CFD and EFD as a research and design methodology. Coordinating the application of both CFD and EFD in a hybrid management approach can expedite results, improve understanding of flow phenomena, and often reduce research costs and time. This paper considers some of the common questions that arise as one considers hybrid research or design methods as it is applied to wind engineering and the built environment.

1. Introduction

Wind Engineering was first identified and defined as a specific subtopic in engineering in the 1975 Freeman lecture prepared by Jack E. Cermak [1]. The application of experimental fluid dynamics (EFD)[1] in fluid modeling facilities (wind or water tunnels) to wind engineering applications began as early as 1891 when Professor la Cour of Denmark established a windmill experimental station at Askov, Denmark. Even earlier in 1759 John Smeaton did experimental investigations of wind effects on solid objects. However, serious application of fluid similarity and physical modeling did not really begin until the 1940–1960 period, when attempts were made to estimate loads on the proposed World Trade Center in New York, the selection of stack heights for power stations, the estimation of flow and dispersion in forests, and the effects of winds and turbulence on pedestrian comfort near buildings and in cities [1,2]. The application of computational fluid dynamics (CFD) to wind engineering occurred somewhat later, since significant software and computational capacity were developed only after about 1960 [3–5].

1.1. Advantages of physical modeling

Wind or water tunnels are, in effect, analog computers that have the advantage of "near-infinitesimal" resolution and "near-infinite memory." A fluid modeling study employs "real fluids" not models of fluids; hence, the fluid model is implicitly non-hydrostatic, turbulent, includes variable fluid properties, non-slip boundary conditions, and dissipation. Real fluids permit flow separation and recirculation. All conservation equations are automatically included in their correct form without truncation or differencing errors, and there are no missing terms or approximations. The basic equations of motion and transport are solved by simulating the flow at a reduced scale, and then the desired quantity is measured. Finally, the fluid model bridges the gap between the fluid-mechanician's analytic or numeric models of flow, turbulence and dispersion and their application in the field. Fluid modeling may be used to plan field experiments, provide conservative estimates of plume transport, wind flows, wind forces, and validate modules of numeric code [6–8]. Some limitations will, of course, exist such as inability to model geophysical scales larger than test facilities.

1.2. Advantages of numerical modeling

Numerical modeling, despite its many limitations associated with grid resolution, choice of turbulence model, or assignment of

---

[1] In this paper experimental fluid dynamics (EFD) will be limited to physical modeling and not full-scale field experiments.

http://dx.doi.org/10.1016/j.buildenv.2015.11.005

boundary conditions is not intrinsically limited by similitude or scale constraints. Thus, in principle, it should be possible to numerically simulate all aspects of fluid motions, thermal stratification, induced forces (such as Coriolis effects), plume transport, dispersion, and/or drift. In addition it should be possible to examine all interactions of these properties individually, sequentially and combined to evaluate nonlinear effects [9,10]. Recently, modelers have even managed to perform down-scaling from meso-scale synoptic programs and up-scaling from surface layer CWE calculations [11,12]. It is this tremendous potential that has led wind engineering practitioners to more frequently present results of such numerical studies in professional and trade journals and promotional materials.

1.3. The CFD/EFD dilemma

Initially the relationship between proponents of CFD and EFD for wind engineering applications, however, was very uneasy. CFD proponents were enthusiastic about the future of their craft, and frequently endorsed numerical methods as the wave of the future, open to immediate use on almost any application, and predicted the eventual demise of “old fashioned” and “surely expensive” and cumbersome fluid modeling facilities. Some predicted that CFD would be dominant by 1985 [13]. Perhaps this is not surprising considering that computer costs were declining by factors of 10 every 5 years. EFD specialists were not convinced. Peter Bradshaw (1975) [14] pointed out that whereas computational number crunching capacity had increased exponentially, our fundamental understanding of turbulence had only grown slowly; hence a “fact gap” which made proposed turbulent models approximate and most numerical results questionable unless carefully validated for the given application. The tendency for many CFD users to believe implicitly in the realism of the beautiful graphical displays that their software produces is implied when one says that CFD is really an acronym for “Colorful Fluid Dynamics.” Harsher critics say that “Cheats, Frauds and Deceivers” would be more appropriate [10].

Since 1960 a number of researchers have reviewed CFD and EFD methods to judge how well they represent the “full scale” or original wind phenomena. Several committees have been formed to systematically examine CFD and EFD reliability and propose minimum domain, boundary conditions, initial conditions, and appropriate turbulence models [15,16]. Other researchers have compiled experimental data sets suitable for validation of CFD models (NPARC Alliance, 2005; ERCOFTAC, 2015; CEDVAL; CSU/TTU Cooperative Program in Wind Engineering, 1987–2002; Architectural Institute of Japan Working Group, 1992–1994) [17–22]. Periodically papers appear that critique CFD methods, consider software verification, and propose validation scenarios [10,21,23–33]. Recently Kraft (2010) [34] even asked the question *“After 40 years why hasn't the computer replaced the wind tunnel?”*

Nonetheless, over the last fifty years the application of CFD to wind engineering (or Computational Wind Engineering, CWE) has matured substantially. The increase in CWE skill parallels the similar growth in fluid-physical or EFD modeling. Cochran and Derickson [33] summarized the sixty year struggle for physical modeling to develop facilities, instrumentation, and model requirements. Today there is general consensus about what one can do with EFD with confidence, what remains uncertain, and what should not be attempted at all. Indeed, EFD for wind engineering went through decades of validation, and so it is not surprising that CWE has followed a similar path. Blocken [3] and Meroney and Derickson [5] have recently reviewed the birth, growing pains, teenage status, and recent maturity of CWE.

A reliable new *hybrid* methodology has arisen that combines the advantages of an old tool, fluid (or physical or scale) modeling (EFD), with the speed and convenience of a new technology, computational fluid dynamics (CFD). The traditional view is that the scientific method has two foundations, experimental and theoretical (Fig. 1). While the traditional scientific method does not acknowledge the role for computing and simulation, a new paradigm establishes a foundation for the extension of the traditional processes to include verification and scientific software development that results in the notional framework known as Sargent's Framework. This framework elucidates the relationships between the processes of scientific model development, computational model verification, and simulation validation (Fig. 2). “The outer circle together with data validity are the technical processes that must be addressed to show that a model is credible … .Assessment activities are spawned from each of these technical processes.” (See Knepell and Arangno, Chapter 2 [35]) For example, fluid modeling can initially provide data from which CFD turbulence models are created, CFD calculations can use such turbulence models to quickly survey alternate solution strategies using simplified domain scenarios, then physical modeling can examine in greater depth design consequences, and finally, CFD can extend initial conclusions to a broader set of similar cases. Combining experiments with numerical simulations also provides new educational opportunities for the next generation of engineers and scientists [36].

Thus, both CFD and EFD are in many respects mature tools to apply to wind engineering. Recently, there has been a courtship between the two methodologies as one identifies how they can complement one another. Indeed, today there are opportunities for a marriage of experimental and numerical technologies. This new discipline has been called “hybrid” wind engineering.

2. Ten questions (and answers) concerning hybrid simulation of the wind environment

Many readers may still feel uncertain as to exactly what this new “hybrid” design dogma entails; hence in the next sections we will consider ten questions about “hybrid” wind engineering research.

2.1. What is hybrid modelling for wind engineering?

Answer: It is the complementary use of CFD and EFD modeling to simulate wind engineering (WE) problems.

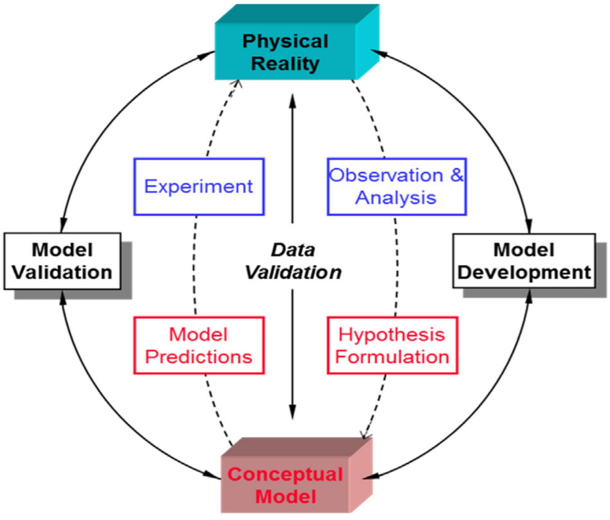

Fig. 1. The “old” scientific method [82].