Urban physics

Inaugural lecture
Prof. Bert Blocken
October 5, 2012

/ Department of the Built Environment

Technische Universiteit
Eindhoven
University of Technology

Urban Physics

Where innovation starts

Inaugural lecture prof. Bert Blocken

Urban Physics

Presented on October 5, 2012
at Eindhoven University of Technology

Urban physics

This inaugural lecture addresses several aspects of urban physics. The lecture starts with definitions of building physics and urban physics, both of which are relatively new scientific disciplines. In fact, urban physics is a sub-discipline of building physics. By means of two examples, the importance of building physics and urban physics for architecture is demonstrated. The past decade has witnessed the rapidly increasing success of the keywords 'building' and 'urban' in scientific journals, publications, lectures and research proposals. This reflects two trends: (1) increasing interest and focus of the wider research community on the urban and building spatial scales; and (2) increased establishment of building physics and urban physics as recognized scientific disciplines with dedicated high impact factor journals and publications. The first trend is further discussed in the light of fading disciplinary boundaries. The second trend is demonstrated by some practical examples. Urban physics entails both basic and applied research. Basic research includes the development of physical models as ingredients of Computational Fluid Dynamics (CFD) codes and simulations. Basic research also includes the investigation of elementary flow phenomena in the built environment, such as the so-called 'Venturi effect' for wind flow in passages between buildings. These basic research efforts are intended to support applied research that aims to benefit our society by contributing to better health, comfort, productivity and well-being. Several topics of applied research are mentioned briefly, in relation to past and present research projects of the urban physics group at Eindhoven University of Technology (TU/e). Some of my views on engineering education in general and on education in urban physics in particular, are also presented. Finally, some future perspectives and acknowledgements are provided.

1. Building physics and urban physics

1.1. Building physics

While technological advances and knowledge of inherited practices have supported the design of buildings and urban areas for centuries, the discipline of building physics only emerged in the 20th century. In these early years, problems of rain penetration, indoor dampness, room acoustics, summer overheating and lighting in buildings were addressed, but often only when really needed or when, after construction of the buildings, problems arose [1]. The first energy crisis of 1973 had a major impact on the establishment of building physics. The related focus on energy efficiency, sustainability and on remediating problems such as rain penetration, moisture problems and mold growth propelled building physics to the forefront of building-related research and education. We adopt the following definition for building physics [2]:

> *"Building physics is the study of the physical behavior of buildings and building components, including the transfer of heat and mass, acoustics, lighting, energy and the indoor and outdoor environment. It is aimed at improving health, comfort and productivity taking into account energetic, ecological and economic constraints."*

In the widest perspective, building physics consists of three sub-disciplines:

1. Building physics of the indoor environment
2. Building physics of the building envelope (facades, windows, roofs, floors)
3. Building physics of the outdoor environment.

1.2. Urban physics

Urban physics can be defined as *building physics of the outdoor environment*. A statement that is often used to justify the importance of *building physics of the indoor environment* is: *"People spend 90% of their time indoors"*. While this is generally true, it also implies that people spend the other 10% outdoors, and also then they need to be comfortable and safe. Furthermore, the outdoor environment determines the indoor environment to a large extent, because a perfect separation between both cannot be achieved. The outdoor environment also interacts with the building envelope. Therefore, urban physics is at least equally important as the two other sub-disciplines of building physics. The following definition is proposed:

> *"Urban physics is the study of the physical aspects of the outdoor urban environment, including the transfer of heat and mass, acoustics, lighting and energy, and their interaction with the indoor environment and the building envelope. It is aimed at improving outdoor and indoor health, comfort, productivity and sustainability taking into account energetic, ecological and economic constraints."*

2. Urban physics and architecture

Urban physics and architecture are strongly intertwined. One cannot go without the other. This is illustrated by means of two examples.

2.1. Facade design, rainwater runoff and surface soiling

> *"All buildings, whatever shortcomings they may have, are required to possess two fundamental characteristics. They should be structurally sound and they should exclude moisture." (Marsh 1977 - [3])*

Wind-driven rain (WDR) is rain that is given a horizontal velocity component by the wind and that is driven against the windward facade of buildings. It is one of the most important moisture sources affecting the hygrothermal performance and durability of building facades [3-9]. Consequences of its destructive properties can take many forms, including rain penetration and the appearance of surface-soiling patterns on facades, which have become characteristic for so many of our buildings. As an example, Figure 1 displays the facade of the Royal Festival Hall in London, before and after a few years of exposure to atmospheric pollution and WDR [4]. The differential soiling pattern is caused by the dry deposition of atmospheric pollutants on the facade and their subsequent relocation by rainwater runoff along the facade. It could be surprising that especially many

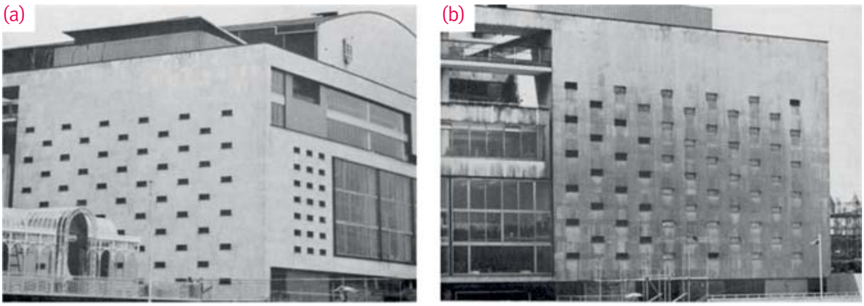

Figure 1

Royal Festival Hall, London. (a) After building completion. (b) After a few years of exposure to atmospheric pollution and wind-driven rain deposition and runoff across the facade (from [4]).

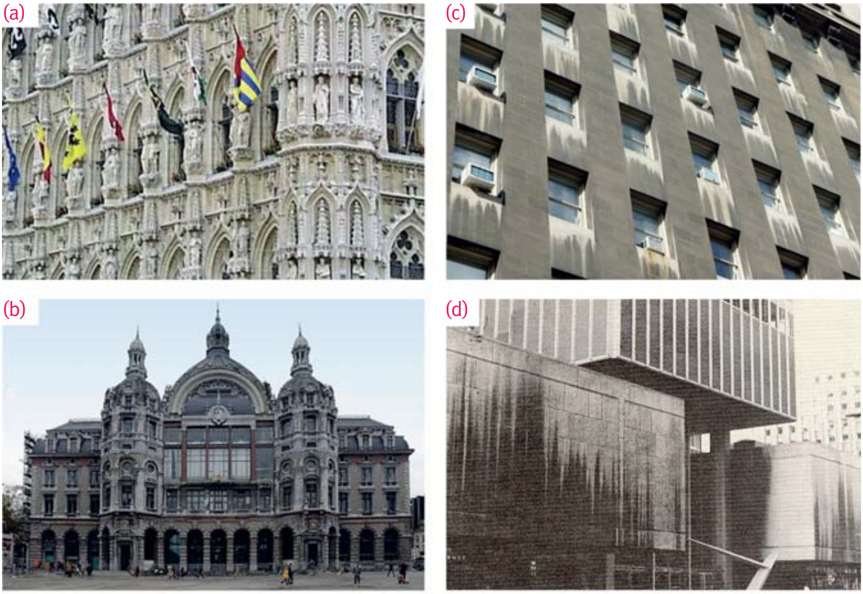

Figure 2

Surface soiling on historical and contemporary buildings: (a-b) Historical buildings with no clearly visible soiling patterns: (a) City Hall, Leuven. (b) Central Railway Station, Antwerp. (c-d) Contemporary buildings with very visible soiling patterns. Dark colors indicate soiled areas, light colors indicate areas that have been cleaned by rainwater runoff (Fig. d from [7]).

contemporary buildings seem to suffer from differential surface soiling, while this appears to be much less pronounced for historical buildings (Figure 2). The reason is explained below.

In the past centuries, buildings were generally designed based on the knowledge of traditional, inherited practices in architecture. Their designs included extensive facade detailing to control rainwater runoff streams and to keep the runoff water away from the underlying facade parts (Figure 2a-b). The well-known ‘drip detail’ for example actually dates back to at least the Romans. In his ‘*Dictionnaire raisonné de l’architecture française du XI^{e} au XVI^{e} siècle*’ (Dictionary of French Architecture from the 11th to the 16th century), the French architect Viollet-le-Duc (1814–1879) [10] discusses the performance of the drip detail accompanied by design drawings. Figure 3 shows the drip of the Roman cornice, which leads the rainwater along the slope *ab*, around the edges *bc* and *cd*, and subsequently along the vertical face *e*, where it is thrown off the wall. The absence of this detail would allow the rainwater to flow along the profiles by surface tension without any obstruction and to reach the vertical facade parts below, resulting in surface soiling and/or rain penetration. This effective detail has been used for centuries.

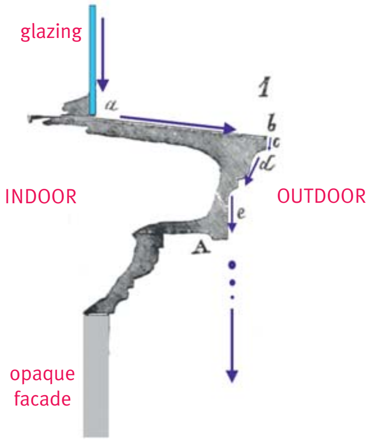

Figure 3

Vertical cross-section of Roman drip detail for rainwater runoff (modified from Violett-Le-Duc [10]).

With the advent of new scientific knowledge, new materials and new technologies in the 19th and especially the 20th century, the fields of architecture and engineering began to separate, with some architects increasingly focusing on aesthetics at the expense of the technical aspects of building design. In their enthusiasm in developing Modern Architecture, several architects actually condemned old construction practice and abandoned facade detailing (such as the drip detail) in their strive towards plane and smooth building facades. One illustration of this is the article by Adolf Loos in 1908, called '*Ornament and Crime*', which was an assault on building facade details [11]. In addition, Le Corbusier (1923) defended the simplicity of forms (purism) [12]. Such points of view were rapidly taken on by developers after the Second World War. In too many cases, the absence of essential facade details in modern building design and construction has led and – even today – continues to lead to buildings that in short periods of time show unacceptable surface soiling, weathering and decay, as shown in Figure 1 and Figure 2c-d. To counter this bleak picture, one should note that modern ideas did not sweep all rational thinking. Auguste Perret, who was as much an architect as a constructor, provided the following reply to a questionnaire of 1934 entitled '*For or Against Ornament*' [13]:

> *"Let us give back to our buildings the organs necessary for their defense against the weather: cornices, string-courses, architraves and moldings, which allow a facade to remain what the artist intended it to be, in spite of the rain."*

However, in the 70's, Robinson and Baker [5] stated that many modern designers were still not sufficiently aware of how natural forces act on their creations and could not predict with any certainty the results of their design decisions. They illustrated:

> *"… the ways in which the intentions of their designers had been negated, usually by the deposition of atmospheric dirt and its dispersal, often random, over wall surfaces by rain water." (Atkinson 1977 [14])*

Unfortunately, this statement is still valid today. In every city, buildings can be found that have suffered extensive facade disfigurement by lack of control of rainwater runoff across the facade.

2.2. High-rise buildings and wind nuisance for pedestrians

High-rise buildings were made possible by the development of steel structures and the invention of the elevator and the water closet. The first modern high-rise buildings for occupation were erected in America near the end of the 19th century. It was only later that high-rise construction entered the European skylines. These buildings were typically erected in cities that were already quite densely composed of low-rise buildings. This situation, with only a few high-rise buildings surrounded by many low-rise buildings, fully exposes the high-rise buildings to the wind. This is exactly the condition that can lead to severe problems of pedestrian-level wind nuisance or even wind danger, as high-rise buildings tend to catch the wind and deviate it down to pedestrian level, as illustrated in Figure 4. This effect of high-rise buildings has surprised their designers. It prompted the beginning of extensive series of aerodynamic studies of pedestrian-level wind conditions around high-rise buildings in wind tunnels, and later by numerical simulation with Computational Fluid Dynamics (CFD).

High wind speed at pedestrian level can be uncomfortable and even dangerous, and detrimental to the success of new buildings and urban areas [16]. Wise [17] reported that shops were left untenanted because of the windy environment that discouraged shoppers. Lawson and Penwarden [18] reported dangerous wind conditions to be responsible for the death of two old ladies blown over by sudden wind gusts near a high-rise building. Many urban authorities nowadays recognize

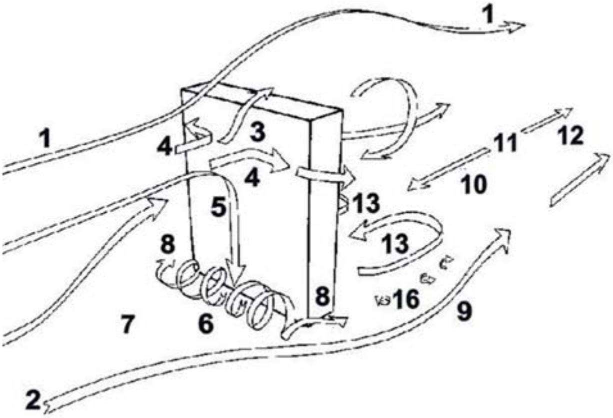

Figure 4

Schematic representation of wind flow around a high-rise building. Pedestrian wind nuisance is generally associated with the standing vortex (indicated with '6') and the corner streams (indicated with '8' and '9') (from [15]).

the importance of pedestrian wind comfort and wind safety and require such studies before granting building permits for new buildings or new urban areas.

In 2006, a Wind Nuisance Standard (NEN 8100) was published in the Netherlands [19,20]. To the best of our knowledge, this is the first Wind Nuisance Standard in the world. It is based on extensive research work by Verkaik [21], Willemsen and Wisse [22,23], Wisse and Willemsen [24] and others. The development and publication of this standard is an important milestone in the history of urban physics research and practice. It is expected that this pioneering effort will be followed by the development of similar standards in many other countries in the years to come.

3. Keywords 'building' and 'urban' in science: from not to hot

Until recently, the words 'building' and 'urban' were often not welcome in well-established disciplinary and interdisciplinary journals on heat and mass transfer, energy, climate and health. The mere use of these words in the title of a paper could be sufficient to find it labeled 'out of scope' by the editor(s). This is only one illustration of the fact that a large part of the academic community has for a long time considered research on buildings as non-scientific and/or not interesting. That situation is now changing. The past decade has witnessed the rapidly increasing success of the keywords 'building' and 'urban' in titles of journals, publications, lectures and research proposals. This reflects two trends: (1) increasing interest and focus of the wider research community on the urban and building spatial scales; and (2) increased establishment of building physics and urban physics as recognized scientific disciplines with dedicated high impact factor journals and publications. The first trend is further discussed in the light of fading disciplinary boundaries in chapter 4. The second trend will be addressed in chapter 5 on 'Publications, citations and impact factors'.

4. Fading disciplinary boundaries

In the past decades, more and more research areas have – at least partly – shifted their interest towards the built environment, i.e. the building and urban spatial scales. This shift is driven by the fact that buildings and cities are at the epicenter of the grand societal challenges energy, climate, health and ageing. Buildings and cities are major energy consumers and therefore they also hold an enormous potential for energy saving. Mitigation of climate change is strongly connected to the energy use of buildings and cities. The same buildings and cities should also be adapted ('climate adaptation') to be able to resist the inevitable part of climate change. Health and comfort in buildings and cities (e.g. air quality) are of increasing concern given the densification of cities, the increasing traffic intensities and the effects of climate change.

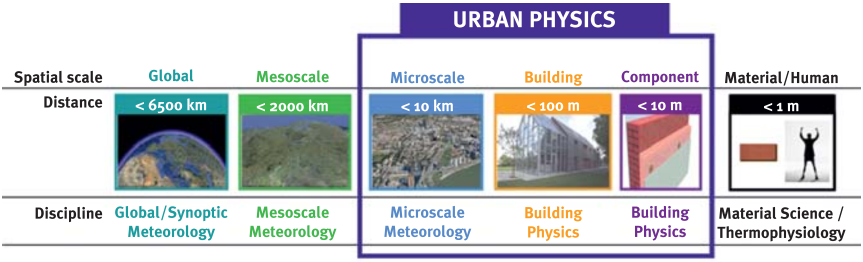

Figure 5

Environmental spatial scales, distances and disciplines.

Figure 5 illustrates the environmental spatial scales and the associated distances and disciplines. Traditionally, research at each of these spatial scales has been practiced by single-scale disciplines within their disciplinary boundaries and with dedicated tools such as single-scale numerical models. In the past decades, these disciplinary boundaries have started to fade, and research activities have become increasingly interdisciplinary and multi-scale. Examples are the increased focus of meso-scale meteorology on the effects of cities and buildings on meteorological processes and the increased focus of material science on the effect of materials on the indoor or outdoor environment of buildings.

5. Publications, citations and impact factors

5.1. Concerns

15 years ago, when I started my academic career, there were only very few academic journals dedicated to building physics, and those that existed had a very low impact factor, and this was also true of the journals in most other areas of building engineering. This has considerably damaged the field, leading some researchers/reviewers from other areas to believe that research in building physics would be of low quality. Building physics and building engineering researchers have responded to the low impact factors of their journals with a multitude of reactions, including (1) denouncing the impact factor as a measure of scientific quality; (2) focusing their efforts on publishing in conference proceedings; and (3) publishing their work in journals in other research areas (and with higher impact factors), which is feasible as far as basic, fundamental and/or generic research efforts are concerned.

The first reaction is not uncommon and is still frequently heard today. Clearly, the impact factor is not an absolute measure of scientific quality. It is certainly inappropriate to compare different research disciplines with each other, because different disciplines often exhibit a very different publication and citation behavior. On the other hand, while one can criticize the impact factor system, the system is here and it appears that it is here to stay for a considerable time to come, given its high degree of penetration into academic funding and evaluation systems and given the absence of better alternatives.

Moreover, the low impact factors of journals in building physics and building engineering in the past were to a large extent *unsurprising* and/or *self-inflicted*, for several reasons. First, building physics is a relatively young discipline, and as result it had no established journals and publication tradition for a long time. At least equally important is the fact that, in building engineering, citing the work of others was sometimes seen as *detracting from the innovative and novel character of one's publication*. It is not uncommon to find past journal and conference papers in building engineering that provide less than five references to the literature, while many more should have been added. This situation is in clear contrast to that in other, more traditional and well-established disciplines, such as medicine and physics. In these disciplines, citing the work of others is generally interpreted as: (1) proof that the author of the present paper is well aware of the state of the art in the field, which reinforces the confidence that the work in the present paper is novel; and (2) a matter of respect and appreciation of the work by others.

5.2. Changes

In the past 15 years, the publication and citation behavior in building physics has changed substantially. This is illustrated by several facts. First, the increased focus of building physics researchers on providing high-quality journal publications, where citing is considered as an indication of the author's knowledge of the state of the art and as a sign of respect for the work by others. Second, a strong increase of the quality of the existing journals, due to the implementation of faster and more thorough review procedures, more stringent evaluation of these reviews by the editors and by the introduction of best-paper awards. An excellent example is the journal *Building and Environment*, where the effective efforts of Editor-in-chief Qingyan Chen and publisher Elsevier have caused the impact factor to undergo an impressive increase from the rather low value of *0.852* in 2007 to the rather high value of *2.400* in 2011. In this case, this increase clearly reflects the strongly increased quality of the journal. Third, in line with more interest from the wider research community for building physics, several new and very promising journals in building physics have been set up, in which fast and thorough review procedures and stringent paper evaluation have also been embedded. An excellent example is the *Journal of Building Performance Simulation*, edited by Jan Hensen and Ian Beausoleil-Morrison.

6. CFD in urban physics

The urban physics group at TU/e and urban physics in general uses different assessment methods, including on-site (field) measurements, reduced-scale wind tunnel measurements and numerical simulation with Computational Fluid Dynamics (CFD), Building Energy Simulation (BES) models and Building-Envelope Heat-Air-Moisture (BE-HAM) transfer models. In the remainder of this inaugural lecture, BES and BE-HAM will not be addressed; the focus concerning numerical tools is on CFD.

On-site measurements offer the advantage that the real situation is studied and the full complexity of the problem is taken into account. However, on-site measurements are usually only performed at a limited number of positions. In addition, there is no or only limited control over the boundary conditions. Reduced-scale wind tunnel measurements allow a strong degree of control over the boundary conditions, however at the expense of – sometimes incompatible – similarity requirements. Furthermore, wind tunnel measurements are usually also only performed in a limited number of positions. CFD on the other hand provides whole-flow field data, i.e. data on the relevant parameters in all points of the computational domain (e.g. [25-27]). Unlike wind tunnel testing, CFD does not suffer from potentially incompatible similarity requirements because simulations can be conducted at full scale. In addition, CFD simulations easily allow parametric studies to evaluate alternative design configurations, especially when the different configurations are all a priori embedded within the same computational domain and grid (see e.g. [28]). However, the accuracy and reliability of CFD are of concern, and verification and validation studies are imperative [25-37]. The high Reynolds numbers and wide range of spatial and temporal scales involved in urban physics do not allow practical application of Direct Numerical Simulation (DNS). Instead, one needs to resort to simplified approaches such as Reynolds-averaged Navier-Stokes (RANS) modeling or Large Eddy Simulation (LES). The physical models used in RANS and LES simulations need to be carefully validated with experimental data that have to satisfy important quality criteria [29,37].

CFD is increasingly used to study a wide range of urban physics processes, such as pedestrian wind comfort and wind safety around buildings [26,35,36,38-43], outdoor air quality [44-53], wind-driven rain [54-64], convective heat transfer [65-67], natural ventilation of buildings [25,28,68-78] and wind energy in the built environment [79,80]. Extensive reviews on the use of CFD in urban physics can be found in [27,42,44,58,77,82-85].

7. Basic research in urban physics

Although building physics and urban physics are essentially applied disciplines, a substantial amount of basic research underlies their successful application. In this chapter, some examples of our basic research are mentioned, one of which is presented in more detail in chapter 8.

- **Quality assurance in CFD: verification and validation**. Verification and validation are essential ingredients of 'best practice' in CFD simulations. While verification focuses on coding errors and numerical errors such as discretization errors, iterative convergence errors and computer round-off errors, validation is intended to determine the extent of physical modeling errors [27,29-37]. In other words: verification addresses the question *'are the equations solved right?'*, while validation addresses the question *'are the right equations being solved?'* [30]. In recent years, our group has contributed substantially to the establishment of best practice guidelines in CFD [26-28,86] and these efforts are increasingly cited in international journal and conference papers.
- **Development of grid generation techniques**. Standard automatic or semi-automatic generation of an unstructured grid does not provide sufficient control of local grid resolution, grid stretching, control volume skewness and aspect ratio. Therefore, a specific grid-generation procedure was presented by van Hooff and Blocken [28]. It consists of a series of grid extrusion operations that allows full control over the grid quality, size and resolution. This technique was first demonstrated by application to the complex geometry of the *Amsterdam ArenA stadium* [28] (Figure 6). Afterwards, it has been used successfully in a wide range of urban physics studies [26,28,43,46,48-50,64,65,74,75,77,78].
- **Development of improved wall functions**. Standard wall functions were developed for equilibrium flow without significant adverse pressure gradients [87] and are generally not suitable for wind flow around buildings in the atmospheric boundary layer, which is characterized by impingement, flow separation and recirculation [88]. We have developed wall function modifications for accurate CFD simulation of atmospheric boundary layer flow [86,89] and for convective heat transfer at building surfaces [90,91].

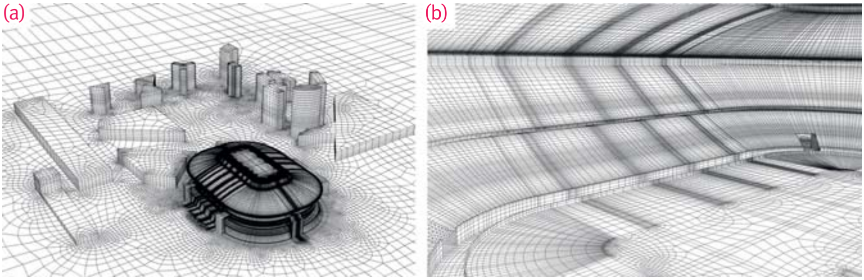

Figure 6

High-resolution and high-quality computational grid of the Amsterdam ArenA stadium and its surroundings: (a) Outdoor. (b) Indoor (van Hooff and Blocken 2010) (from [28]).

- **Investigation of basic flow phenomena in the built environment**. Wind flow in the built environment is very complex [88]. Our research has shown that the interaction between wind and buildings in the atmospheric boundary layer can yield strong counter-intuitive effects [75,92-95]. The next chapter presents an example.

8. Venturi effect between buildings: fact or fiction?

Different definitions of the Venturi effect can be found in the literature. In this inaugural lecture and in urban physics, we extract the definition from the original book of Giovanni Battista Venturi (1799 - [96]): The Venturi effect refers to the increase of fluid speed when flowing through a contraction and this increase is proportional to the decrease in cross-sectional area. This is illustrated in Figure 7a. The Venturi effect applies to *confined* flows.

The term 'Venturi effect' has been used often [97,98] and is still very frequently used by building engineers and architects to refer to wind flow in passages between buildings. A typical example is a passage between two buildings in a

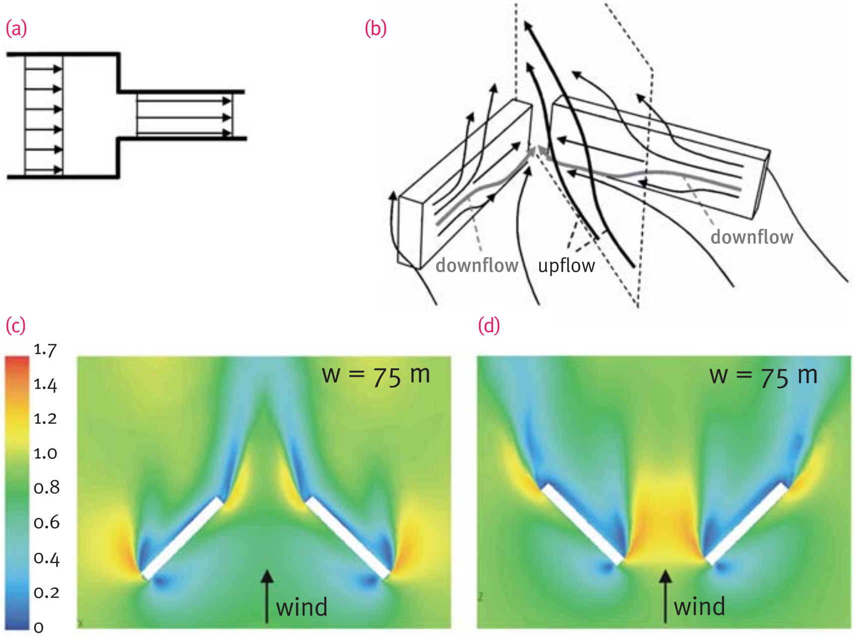

Figure 7

(a) Schematic representation of Venturi effect in a closed channel. (b) Schematic representation of wind flow around a converging building arrangement. (c-d) Wind speed amplification factors in a horizontal plane at pedestrian height for (c) converging and (d) diverging building arrangement (Blocken et al. 2008) (from [93]).

so-called *converging arrangement*, also referred to as ‘Venturi throat’ (Figure 7b). However, the validity of the term Venturi effect for wind flow around buildings can be questioned because these flows are *open flows*, not confined flows, and there is no law in physics that states that all approaching wind should go through the narrow passage. As shown in Figure 7b, the wind can also flow around and over the buildings. Which fraction of the approaching wind will flow through the passage and which fraction will flow around and over the buildings is, to a large extent, determined by the resistance of the different flow paths. Let us focus on Figure 7c and 7d that show CFD simulation results for wind flow around two buildings in a converging and a diverging arrangement. The buildings are each 100 m long, 30 m high and 10 m wide. The contour plots illustrate the amplification factor, i.e. the ratio of the local wind speed to the wind speed that would occur without buildings present (i.e. in free-field conditions). Contrary to what would be expected from the Venturi effect, the acceleration of the wind is most pronounced in the passage of the diverging arrangement, not the converging arrangement. The reason is that the converging arrangement provides a larger resistance for flow through the passage. As a result, a larger part of the oncoming wind flows around and over the buildings in Figure 7b, rather than being forced through the passage. We have called this counter-intuitive effect the ‘wind-blocking’ effect and have confirmed it by detailed wind tunnel experiments and CFD simulations for a wide range of building configurations [93,94]. If the Venturi effect were acting, one would at least expect that the flow rate through the converging passage would be higher than the flow rate in free-field conditions. However, the aerodynamic studies have shown exactly the opposite [93]: for every single configuration that was studied, the flow rate through the converging passage was always lower than the free-field flow rate. The reason is the wind-blocking effect, not the Venturi effect.

9. Applied research and valorization in urban physics

Some examples of applied research and valorization are mentioned below, in relation to past and present research projects of the urban physics group at TU/e. These applied research efforts are essentially supported by the basic research, part of which was mentioned in chapter 7.

- **Wind comfort and wind safety for pedestrians** are important requirements in urban areas. Wind comfort assessment with the Dutch Wind Nuisance Standard and with CFD was performed for different case studies, including the Amsterdam ArenA Boulevard [43], Eindhoven city center (Figure 8) and the TU/e campus [26] (Figure 9).
- **Wind conditions in harbors** are important for ship maneuvering, harbor accessibility and harbor safety. To support the further expansion of the Port of Rotterdam as the largest harbor in Europe, an extensive computational model was developed (Figure 10) and the CFD simulations were validated with detailed on-site measurements. The simulation results will be used for real-time maneuvering operations and for training of harbor pilots.
- **Natural ventilation** is an important sustainable ventilation strategy for buildings. It is particularly important for very large indoor environments such as the multifunctional Amsterdam ArenA soccer stadium, where traditional HVAC systems (Heating, Ventilation and Air-Conditioning) are not feasible.

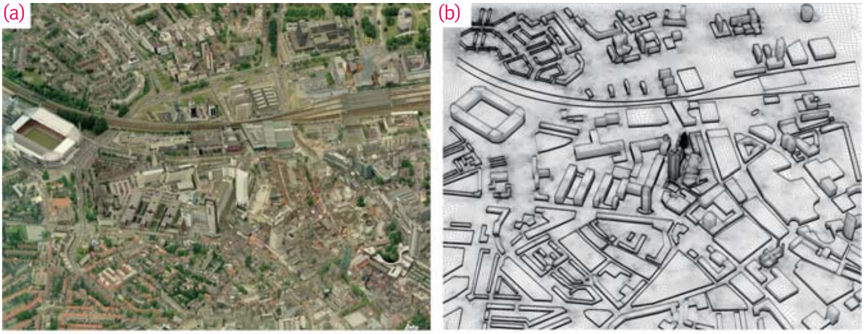

Figure 8

(a) Aerial photograph and (b) computational grid of Eindhoven city center (Janssen, Blocken, van Hooff 2012).

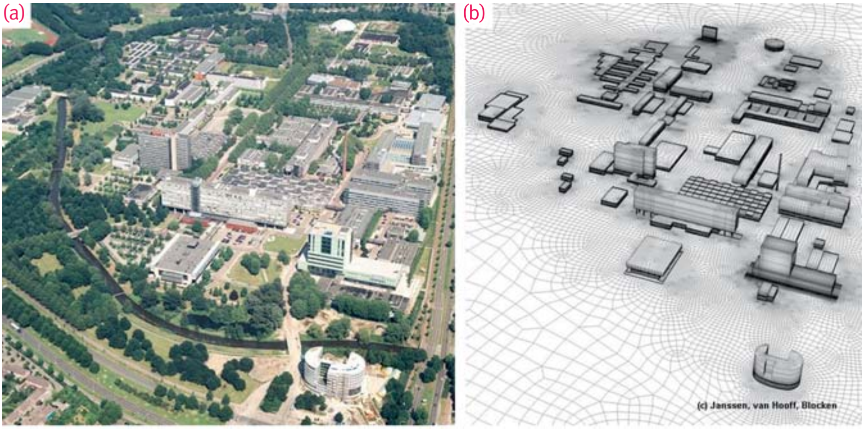

Figure 9

(a) Aerial photograph and (b) computational grid of the campus of Eindhoven University of Technology (situation 2010) (Janssen, Blocken, van Hooff 2012) (from [26]).

Figure 6 illustrates part of the computational grid that successfully indicated how to substantially improve the natural ventilation of the stadium [28].

- **Outdoor air quality** is a major concern in many cities world-wide. In collaboration with Concordia University in Montreal, a high-resolution computational model of part of downtown Montreal was developed and the dispersion of air pollution was numerically simulated. The model results were validated based on detailed on-site measurements and wind tunnel measurements of pollutant gas dispersion [48,99].
- **Wind energy in the built environment**. The wind energy potential in passages between buildings has been analyzed, including an a posteriori optimization of the Bahrain World Trade Center. Also the wind energy and natural ventilation potential of the Venturi-shaped roof invented by Bronsema [100,101] has been optimized. Detailed CFD simulations and wind tunnel measurements showed that adding vertical guiding vanes, irrespective of their number, would completely cancel the effect of the roof [75,95]. The configuration without guiding vanes on the other hand was shown to be very effective, increasing the mean wind speed up to 50%. The reason for this counter-intuitive observation is very similar to that outlined in chapter 8: adding the vertical guiding vanes increases the flow resistance in the roof. As a result, the flow will for a large part flow around and over the roof, rather than being forced through the funnels in the roof (wind-blocking effect).
- **Urban heat island effect**. The urban heat island (UHI) effect refers to the increase in temperature in urban areas compared to rural areas [102,103].

Steeneveld et al. [104] have shown that most Dutch cities experience a substantial UHI effect and similar observations have been made in other countries. Our group is currently developing high-resolution computational grids (as shown in Figures 8 and 9) for numerically assessing the UHI effect as well as evaluating mitigation measures for several cities in the Netherlands and Belgium.

- **Adaptation to climate change**. In the extensive research program ‘Climate Proof Cities’ (part of Knowledge for Climate), a consortium with research partners and city and regional authorities is collaborating intensively to

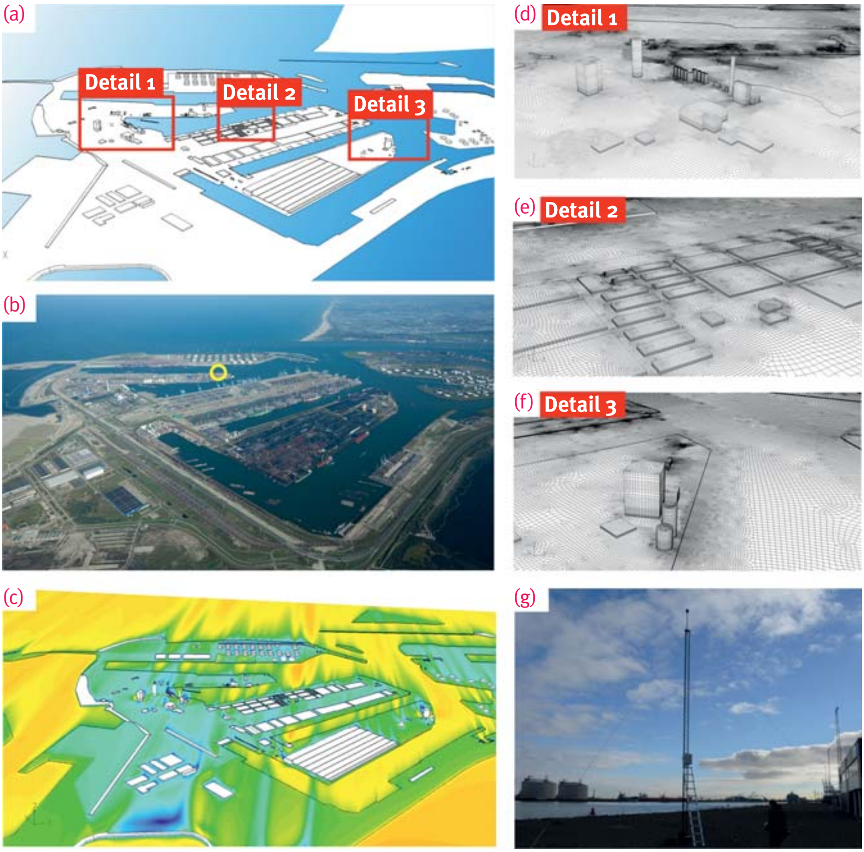

Figure 10

(a-b) Geometry of Maasvlakte 1 of Port of Rotterdam, with measurement position nr. 3 indicated by yellow circle in fig. b, referring to fig. g. (c) Contours of mean wind speed over the study area (colorbar and units omitted intentionally). (d-f) Details of high-resolution computational grid. (g) Measurement position at Yangtzehaven Zuid (Janssen, Blocken, van Wijhe 2012).

investigate the urban climate in Dutch cities, to determine the potential impacts of climate change, to analyze the effectiveness of remedial measures and to develop governance strategies for implementation of these measures. TU/e is a key partner in this consortium. This integral and multi-scale research program covers most of the spatial scales in Figure 5.

- **Other topics**: Other topics include applications outside urban physics, such as cyclist aerodynamics, gas dispersion around ships, naval aerodynamics for off-shore helicopter landing operations and ventilation of indoor enclosures with jets at laminar, transitional and turbulent slot Reynolds numbers. All these applications are supported by basic research.

10. Education

Education is the opportunity to educate the next generation of professionals that will shape the society of the future. High-quality education is a key mission of the university and the moral duty of every university lecturer. Teaching and research are strongly intertwined. Teaching is educating the next generation of researchers. Research allows students to be educated with not only the established basic knowledge but also with the latest findings in the field. Research can also illustrate why knowledge and a solid education are so important.

In every engineering discipline, high-quality education should include a solid basis in mathematics, physics and chemistry. The importance of this basis can hardly be overemphasized. In this respect, I would like to rephrase the quote by Brander Matthews (1852-1929), which he formulated in support of educating students in Latin, as follows, now in support of educating students in mathematics:

> *"An engineer need not know how to solve partial differential equations, but (s)he should at least have forgotten it."*

As illustrated in chapter 2, building physics and architecture are strongly intertwined. One cannot go without the other. The embedment of this inextricable connection in the education of architects and building engineers is imperative. Building physics without architecture is an applied discipline without application. Architecture without building physics is art without the required physical and technological background to achieve the intended performance.

For the courses in *Urban Physics* and *Computational Fluid Dynamics* that I currently teach at the Department of the Built Environment, a background in mathematics and physics, with a focus on fluid mechanics, is essential. In those cases where my students do not have this background, my first classes to them consist of the Greek alphabet and a crash course in fluid statics, kinematics and dynamics. Surely, this is not sufficient. Therefore, in addition, they should at least study the important basic fluid dynamics courses in the Department of Applied Physics and/or the Department of Mechanical Engineering.

11. Conclusions and future perspectives

Urban physics is the interdisciplinary and multi-scale study of physical processes in urban environments. It is positioned at the epicenter of the grand societal challenges energy, climate, health and ageing and it covers a wide range of spatial scales. Therefore, the interest of the wider research community in building-scale and urban-scale physical processes and the importance of urban physics are expected to continue to increase substantially in the coming decades.

In urban physics, the combination of CFD and experiments is important and can yield strong synergetic effects. Excellent research in urban physics and building physics is not possible without access to appropriate experimental research facilities and highly-skilled technical staff to operate these facilities. Maintaining and even expanding experimental research facilities is an important challenge for the future.

Urban physics processes are too complex to be grasped by intuition. The examples in chapter 8 and 9 on the Venturi effect versus the wind-blocking effect have shown that even in these very simple cases of isothermal wind flow around basic building configurations or roofs, the actual flow behavior can be complicated and counter-intuitive. This complexity reinforces the importance of accurate assessment tools: high-quality on-site experiments, high-quality wind tunnel experiments and high-quality CFD simulations that have undergone intensive verification and validation.

The interdisciplinary and multi-scale character of urban physics provides ample opportunity for collaboration with other disciplines. In the future, as the urban physics group at TU/e, we will continue to build and expand collaboration with strong partners with complementary expertise. At TU/e, the successful collaboration with the Fluid Dynamics Laboratory of the Department of Applied Physics will be continued and expanded. The same holds for the successful collaboration with other key national and international university partners, with the leading research institutes TNO[1], VKI[2], MARIN[3], DNW-NLR[4], VITO[5], Deltares and others, and with a wide range of important authorities and companies (Port of Rotterdam, Heijmans, Biddle, Peutz, ANSYS, the Flemish Cycling Union and others).

1 TNO = Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Scientific Research)
2 VKI = Von Karman Institute for Fluid Dynamics
3 MARIN = Maritime Research Institute Netherlands
4 DNW-NLR = Duits-Nederlandse Windtunnels – Nationaal Lucht- en Ruimtevaart Laboratorium (German-Dutch Wind Tunnels – National Aerospace Laboratory)
5 VITO = Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research)

12. Boundary conditions rule the world

Boundary conditions rule the world. As an example, the physical aspects of any fluid flow are governed by three fundamental physical principles and their corresponding governing equations: conservation of mass, Newton's second law and conservation of energy. Whether we study the wind-flow pattern around a building or the flow of a raindrop running down a glass pane, these equations are always the same, although the types of flow are completely different. The reasons for this are the boundary conditions. It is the boundary conditions that are different and that determine which physical phenomena intervene and what happens.

Boundary conditions rule the world. Many of my research efforts in the past 15 years have focused on developing boundary conditions for solving atmospheric boundary layer flow based on the Navier-Stokes equations. It is known that the quality of the boundary conditions determines to a very large extent whether a simulation is successful or not. In turn, as a person I have had the pleasure and privilege of being subjected to many high-quality boundary conditions. This chapter is a tribute to these boundary conditions.

The four colleagues with whom I have worked most intensively, in the past 15 years, are (in alphabetical order of last name):

- Prof.dr.ir. Jan Carmeliet, the former supervisor of my PhD thesis at KU Leuven.
- Prof.dr.ir. GertJan van Heijst, who prompted the strong and successful collaboration between our research groups at TU/e.
- Prof.dr.ir. Jan Hensen, the chairman of the Unit Building Physics and Services (BPS) and the chairman of the appointment committee that recruited me as assistant professor to the department at TU/e in 2006.
- Prof.dr. Ted Stathopoulos, whose group I joined in 2005 at the Department of Building, Civil and Environmental Engineering at Concordia University in Montreal.

Their confidence and support has been invaluable for my career and for building the new urban physics research group at TU/e. We have collaborated intensively by co-supervising PhD and MSc students, co-organizing courses and conferences

and writing a large number of journal and conference papers together. I hope that this collaboration will continue for many years to come.

I am blessed with exceptionally talented and dedicated PhD students, MSc students and a postdoctoral fellow. It is really nearly impossible for me to imagine a better group and I am very proud of these fantastic individuals. Special thanks therefore go to ir. Twan van Hooff, ir. Pierre Gousseau, ir. Wendy Janssen, ir. Rubina Ramponi (Politecnico di Milano), ir. Hamid Montazeri, ir. Mike van der Heijden, ir. Thijs van den Brande (KU Leuven), ir. Aytac Kubilay (ETH Zurich) and ir. Okke Bronkhorst for their commitment, confidence, excellent research work and for our successful and enjoyable collaboration. Special thanks also go to the recent group members dr. Christof Gromke, ir. Adelya Khayrullina and ir. Yasin Toparlar, for their confidence and for having chosen to join and reinforce my urban physics group.

I thank the former and present Eindhoven University Board (College van Bestuur), Departmental Board (Faculteitsbestuur Bouwkunde) and the Board of Deans (College van Decanen) for their confidence and support in appointing me as full professor and chair of Building Physics.

I am very grateful to the IWT-Flanders (Agency for Innovation by Science and Technology in Flanders, Belgium) for having supported the early stages of my career with a 4-year PhD scholarship, granted in 1998. I am also very grateful to the FWO-Flanders (Research Fund - Flanders, Belgium) for having granted me the FWO Postdoctoral Fellowship in 2004 that allowed me to further develop this academic career. Without their support, I would not be here today.

I want to express my gratitude for the confidence, support and successful collaboration with all my colleagues at universities, research institutes, government bodies and companies with whom I have had the pleasure of collaborating. Far too many to mention them all, but this certainly does not detract from the great respect and appreciation I have for them. In particular, I want to express my gratitude to all partners in the very successful TNO-led Climate Proof Cities Consortium (part of Knowledge for Climate) for their confidence in me and for the great collaboration. I also thank all PhD and MSc students that I have (co-)supervised at different universities in the past 15 years.

I am especially grateful for the excellent experimental and computational support by the Laboratory of the unit Building Physics and Services (BPS) headed by

Jan Diepens, for the excellent administrative support by the secretariat of the unit BPS (Renée van Geene and Janet Smolders) and for the excellent support by the secretariat and administrative services of our department and university. Their every-day and high-quality support to provide us with the best possible boundary conditions is deeply appreciated.

Last, but certainly not least, my heart goes out to my friends and to my family, especially to my parents. No words can express how important your support is to me. Thanks for your care, your patience, your understanding.

Boundary conditions rule the world. Thanks, all of you. You are the best boundary conditions.

Ik heb gezegd.

References

1. Hens HSLC. 2007. Building Physics: Heat, Air and Moisture. Wiley.
2. Hens HSLC. 2003. Bouwfysica: Warmte- en Massatransport (in Dutch). Acco, Leuven.
3. Marsh P. 1977. Air and rain penetration of buildings. The Construction Press Ltd., Lancaster, England. 174 p.
4. White RB. 1967. The changing appearance of buildings. HMSO, London, 64 p
5. Robinson G, Baker MC. 1975. Wind-driven rain and buildings. National Research Council of Canada, Division of Building Research, Technical Paper No. 445, Ottawa.
6. Eldridge HJ. 1976. Common defects in buildings. HMSO, 486 p.
7. El-Shimi M, White R, Fazio P. 1980. Influence of facade geometry on weathering. Can J Civil Eng 7(4): 597-613.
8. Franke L, Schumann I, van Hees R, van der Klugt L, Naldini S, Binda L et al. 1998. Damage atlas: classification and analyses of damage patterns found in brick masrony. European Commission Research report nr. 8, vol. 2, Fraunhofer IRB Verlag
9. Blocken B, Carmeliet J. 2004. A review of wind-driven rain research in building science. J. Wind Eng. Ind. Aerodyn. 92(13): 1079-1130.
10. Viollet-le-Duc E. 1868. Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle, Tome 6, A. Morel editor, Paris.
11. Collins P. 1959. Concrete: the Vision of a New Architecture. New York Horizon Press.
12. Le Corbusier. Toward an Architecture (Verse une Architecture). Translated by John Goodman. Los Angeles: Getty Research Institute, 2007.
13. Collins P. 1965. Changing Ideals in Modern Architecture. 1750-1950. Montreal, McGill University Press.
14. Atkinson GA. 1977. External vertical surfaces of buildings: aspects of design and appearance. RILEM/ASTM/CIB Symposium on Evaluation of the Performance of External Vertical Surfaces of Buildings. OTANIEMI, Espoo, Finland. August 28-31, 1977, and September 1-2, 1977, Volume 1.
15. Beranek WJ, van Koten H. 1979. Beperken van windhinder om gebouwen, deel 1, Stichting Bouwresearch no. 65, Kluwer Technische Boeken BV, Deventer (in Dutch).
16. Durgin FH, Chock AW. 1982. Pedestrian wind levels: a brief review. Journal of the Structural Division ASCE 108 ST8: 1751–1767
17. Wise AFE. 1970. Wind effects due to groups of buildings, Proceedings of the Royal Society Symposium Architectural Aerodynamics, Session 3, Effect of Buildings on the Local wind, London. pp. 26–27 February.
18. Lawson TV, Penwarden AD. 1975. The effects of wind on people in the vicinity of buildings, Proceedings 4th International Conference on Wind Effects on Buildings and Structures, Cambridge University Press, Heathrow, pp. 605–622.
19. NEN 2006. Wind comfort and wind danger in the built environment, NEN 8100 (in Dutch) Dutch Standard.
20. NEN 2006. Application of mean hourly wind speed statistics for the Netherlands, NPR 6097:2006 (in Dutch). Dutch Practice Guideline.
21. Verkaik JW. 2006. On wind and roughness over land. PhD thesis. Wageningen University. The Netherlands, 123 p.

22. Willemsen E, Wisse JA. 2002. Accuracy of assessment of wind speed in the built environment. J. Wind Eng. Ind. Aerodyn. 90: 1183-1190.
23. Willemsen E, Wisse JA. 2007. Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. J. Wind Eng. Ind. Aerodyn. 95(9-11): 1541-1550.
24. Wisse JA, Willemsen E. 2003. Standardization of wind comfort evaluation in the Netherlands. 11th Int. Conf. Wind Eng. (11ICWE), Lubbock, Texas.
25. Chen Q. 2009. Ventilation performance prediction for buildings: A method overview and recent applications. Build. Environ. 44(4): 848-858.
26. Blocken B, Janssen WD, van Hooff T. 2012. CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus. Environ. Modell. Softw. 30: 15-34.
27. Blocken B, Gualtieri C. 2012. Ten iterative steps for model development and evaluation applied to Computational Fluid Dynamics for Environmental Fluid Mechanics. Environ. Modell. Softw. 33: 1-22.
28. van Hooff T, Blocken B. 2010. Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium. Environ. Modell. Softw. 25 (1), 51-65.
29. Schatzmann M, Rafailidis S, Pavageau M. 1997. Some remarks on the validation of small-scale dispersion models with field and laboratory data. J. Wind Eng. Ind. Aerodyn. 67-68: 885-893.
30. Roache PJ. 1997. Quantification of uncertainty in computational fluid dynamics. Annu. Rev. Fluid Mech. 29: 123-160.
31. Casey M, Wintergerste T. 2000. Best Practice Guidelines, ERCOFTAC Special Interest Group on Quality and Trust in Industrial CFD, ERCOFTAC, Brussels.
32. Stathopoulos T. 2002. The numerical wind tunnel for industrial aerodynamics: real or virtual in the new millennium? Wind Struct. 5(2–4): 193–208.
33. Oberkampf WL, Trucano TG, Hirsch C. 2004. Verification, validation, and predictive capability in computational engineering and physics. Appl. Mech. Rev. 57(5): 345-384.
34. Jakeman AJ, Letcher RA, Norton JP. 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Modell. Softw. 21(5): 602-614.
35. Franke J, Hellsten A, Schlünzen H, Carissimo B. 2007. Best practice guideline for the CFD simulation of flows in the urban environment. COST 732: Quality Assurance and Improvement of Microscale Meteorological Models.
36. Tominaga Y, Mochida A, Yoshie R, Kataoka H, Nozu T, Yoshikawa M, Shirasawa T. 2008. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. J. Wind Eng. Ind. Aerodyn. 96(10-11): 1749-1761.
37. Schatzmann M, Leitl B. 2011. Issues with validation of urban flow and dispersion CFD models. J. Wind Eng. Ind. Aerodyn. 99(4): 169-186.
38. Stathopoulos T, Baskaran A. 1996. Computer simulation of wind environmental conditions around buildings. Eng. Struct. 18(11): 876–885.
39. Richards PJ, Mallison GD, McMillan D, Li YF. 2002. Pedestrian level wind speeds in downtown Auckland. Wind Struct. 5(2-4): 151-164.
40. Blocken B, Roels S, Carmeliet J. 2004. Modification of pedestrian wind comfort in the Silvertop Tower passages by an automatic control system. J. Wind Eng. Ind. Aerodyn. 92 (10): 849-873.
41. Yoshie R, Mochida A, Tominaga Y, Kataoka H, Harimoto K, Nozu T, Shirasawa T. 2007. Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. J. Wind Eng. Ind. Aerodyn. 95(9-11): 1551-1578.
42. Mochida A, Lun IYF. 2008. Pedestrian wind environment and thermal comfort at pedestrian level in urban area. J. Wind Eng. Ind. Aerodyn. 96: 1498-1527.

43. Blocken B, Persoon J. 2009. Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard. J. Wind Eng. Ind. Aerodyn. 97(5-6): 255-270.
44. Meroney RN. 2004. Wind tunnel and numerical simulation of pollution dispersion: a hybrid approach. Working paper, Croucher Advanced Study Insitute on Wind Tunnel Modeling, Hong Kong University of Science and Technology, 6-10 December, 2004, 60 pp.
45. Hanna SR, Brown MJ, Camelli FE, Chan ST, Coirier WJ, Hansen OR, Huber AH, Kim S, Reynolds RM. 2006. Detailed simulations of atmospheric flow and dispersion in downtown Manhattan. An application of five computational fluid dynamics models. Bull. Am. Met. Soc. 87: 1713-1726.
46. Blocken B, Stathopoulos T, Saathoff P, Wang X. 2008. Numerical evaluation of pollutant dispersion in the built environment: comparisons between models and experiments. J. Wind Eng. Ind. Aerodyn. 96(10-11): 1817-1831.
47. Gromke C, Buccolieri R, Di Sabatino S, Ruck B. 2008. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data. Atmos. Environ. 42(37): 8640-8650.
48. Gousseau P, Blocken B, Stathopoulos T, van Heijst GJF. 2011. CFD simulation of near-field pollutant dispersion on a high-resolution grid: a case study by LES and RANS for a building group in downtown Montreal. Atmos. Environ. 45(2): 428-438.
49. Gousseau P, Blocken B, van Heijst GJF. 2011. CFD simulation of pollutant dispersion around isolated buildings: On the role of convective and turbulent mass fluxes in the prediction accuracy. J. Hazard. Mater. 194: 422-434.
50. Gousseau P, Blocken B, van Heijst GJF. 2012. Large-Eddy Simulation of pollutant dispersion around a cubical building: Analysis of the turbulent mass transport mechanism by unsteady concentration and velocity statistics. Environ. Pollution 167: 47-57.
51. Tominaga Y, Stathopoulos T. 2009. Numerical simulation of dispersion around an isolated cubic building: Comparison of various types of k-e models. Atmos. Environ. 43(20): 3200-3210.
52. Tominaga Y, Stathopoulos T. 2010. Numerical simulation of dispersion around an isolated cubic building: Model evaluation of RANS and LES. Build. Environ. 45(10): 2231-2239.
53. Tominaga Y, Stathopoulos T. 2011. CFD modeling of pollution dispersion in a street canyon: Comparison between LES and RANS. J. Wind Eng. Ind. Aerodyn. 99(4): 340-348.
54. Choi ECC. 1993. Simulation of wind-driven rain around a building. J. Wind Eng. Ind. Aerodyn. 46&47: 721-729.
55. Etyemezian V, Davidson CI, Zufall M, Dai W, Finger S, Striegel M. 2000. Impingement of rain drops on a tall building. Atmos. Environ. 34(15): 2399-2412.
56. van Mook FJR. 2002. Driving rain on building envelopes, Ph.D. thesis, Building Physics and Systems, Eindhoven University of Technology, Eindhoven University Press, Eindhoven, The Netherlands, 198 p.
57. Blocken B, Carmeliet J. 2002. Spatial and temporal distribution of driving rain on a low-rise building. Wind Struct. 5(5): 441-462.
58. Blocken B, Carmeliet J. 2004. A review of wind-driven rain research in building science. J. Wind Eng. Ind. Aerodyn. 92(13): 1079-1130.
59. Blocken B, Carmeliet J. 2007. Validation of CFD simulations of wind-driven rain on a low-rise building. Build. Environ. 42(7): 2530-2548.
60. Blocken B, Carmeliet J. 2010. Overview of three state-of-the-art wind-driven rain assessment models and comparison based on model theory. Build. Environ. 45 (3): 691-703.
61. Tang W, Davidson CI. 2004. Erosion of limestone building surfaces caused by wind-driven rain. 2. Numerical modelling. Atmos. Environ. 38(33): 5601-5609.
62. Briggen PM, Blocken B, Schellen HL. 2009. Wind-driven rain on the facade of a monumental tower: numerical simulation, full-scale validation and sensitivity analysis. Build. Environ. 44(8): 1675-1690.

63. Huang SH, Li QS. 2010. Numerical simulations of wind-driven rain on building envelopes based on Eulerian multiphase model. J. Wind Eng. Ind. Aerodyn. 98(12): 843-857.
64. van Hooff T, Blocken B, van Harten M. 2011. 3D CFD simulations of wind flow and wind-driven rain shelter in sports stadia: influence of stadium geometry. Build. Environ. 46(1): 22-37
65. Blocken B, Defraeye T, Derome D, Carmeliet J. 2009. High-resolution CFD simulations of forced convective heat transfer coefficients at the facade of a low-rise building. Build. Environ. 44(12): 2396-2412.
66. Defraeye T, Blocken B, Carmeliet J. 2010. CFD analysis of convective heat transfer at the surfaces of a cube immersed in a turbulent boundary layer. Int. J. Heat Mass Transfer 53(1-3): 297-308.
67. Karava P, Jubayer CM, Savory E. 2011. Numerical modelling of forced convective heat transfer from the inclined windward roof of an isolated low-rise building with application to Photovoltaic/Thermal systems. Appl. Therm. Eng. 31(11-12): 1950-1963.
68. Kato S, Murakami S, Takahashi T, Gyobu T. 1997. Chained analysis of wind tunnel test and CFD on cross ventilation of large-scale market building. J. Wind Eng. Ind. Aerodyn. 67-68: 573-587.
69. Jiang Y, Chen Q. 2002. Effect of fluctuating wind direction on cross natural ventilation in buildings from large eddy simulation. Build. Environ. 37(4): 379-386.
70. Heiselberg P, Li Y, Andersen A, Bjerre M, Chen Z. 2004. Experimental and CFD evidence of multiple solutions in a naturally ventilated building. Indoor Air 14(1): 43-54.
71. Hu CH, Ohba M, Yoshie R. 2008. CFD modelling of unsteady cross ventilation flows using LES. J. Wind Eng. Ind. Aerodyn. 96: 1692-706.
72. Evola G, Popov V. 2006. Computational analysis of wind driven natural ventilation in buildings. Energ. Build. 38: 491-501.
73. Moonen P, Dorer V, Carmeliet J. 2011. Evaluation of the ventilation potential of courtyards and urban street canyons using RANS and LES. J. Wind Eng. Ind. Aerodyn. 99(4): 414-423.
74. van Hooff T, Blocken B. 2010. On the effect of wind direction and urban surroundings on natural ventilation of a large semi-enclosed stadium. Comput. Fluids 39: 1146-1155.
75. van Hooff T, Blocken B, Aanen L, Bronsema B. 2011. A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. Build. Environ. 46(9): 1797-1807.
76. Norton T, Grant J, Fallon R, Sun DW. 2010. Optimising the ventilation configuration of naturally ventilated livestock buildings for improved indoor environmental homogeneity. Build. Environ. 45(4): 983-995.
77. Ramponi R, Blocken B. 2012. CFD simulation of cross-ventilation for a generic isolated building: impact of computational parameters. Build. Environ. 53: 34-48.
78. Ramponi R, Blocken B. 2012. CFD simulation of cross-ventilation flow for different isolated building configurations: validation with wind tunnel measurements and analysis of physical and numerical diffusion effects. J. Wind Eng. Ind. Aerodyn. 104-106: 408-418.
79. Campbell NS, Stankovic S. Wind energy for the Built environment–Project WEB, A report for Joule III Contract No JOR3-CT98-01270 2001.
80. Balducci F, Bianchini A, Ferrari L. 2012. Microeolic turbines in the built environment: Influence of the installation site on the potential energy yield. Renew. Energ. 45: 163-174.
81. Blocken B, Carmeliet J. 2004. Pedestrian wind environment around buildings: Literature review and practical examples. J. Therm. Env. Build. Sci. 28(2): 107-159.
82. Hanjalic K, Kenjeres S. 2008. Some developments in turbulence modeling for wind and environmental engineering. J. Wind Eng. Ind. Aerod. 96(10-11): 1537-1570.
83. Blocken B, Stathopoulos T, Carmeliet J, Hensen JLM. 2011. Application of CFD in building performance simulation for the outdoor environment: an overview. J. Build. Perform. Simul. 4(2): 157-184.

84. Moonen P, Defraeye T, Dorer V, Blocken B, Carmeliet J. 2012. Urban physics: effect of the microclimate on comfort, health and energy demand. Frontiers of Architectural Research. In press.
85. Defraeye T, Blocken B, Derome D, Nicolai B, Carmeliet J. 2012. Convective heat and mass transfer modelling at air-porous material interfaces: overview of existing methods and relevance. Chem. Eng. Sci. 74: 49–58.
86. Blocken B, Stathopoulos T, Carmeliet J. 2007. CFD simulation of the atmospheric boundary layer: wall function problems. Atmos. Environ. 41(2), 238-252.
87. Launder BE, Spalding DB. 1974. The numerical computation of turbulent flows. Comput. Meth. Appl. Mech. Eng. 3: 269-89.
88. Murakami S. 1993. Comparison of various turbulence models applied to a bluff body. J. Wind Eng. Ind. Aerodyn. 46&47: 21-36.
89. Blocken B, Carmeliet J, Stathopoulos T. 2007. CFD evaluation of the wind speed conditions in passages between buildings – effect of wall-function roughness modifications on the atmospheric boundary layer flow. J. Wind Eng. Ind. Aerodyn. 95(9-11): 941-962.
90. Defraeye T, Blocken B, Carmeliet J. 2011. An adjusted temperature wall function for turbulent forced convective heat transfer for bluff bodies in the atmospheric boundary layer. Build. Environ. 46(11): 2130-2141.
91. Defraeye T, Blocken B, Carmeliet J. 2012. CFD simulation of heat transfer at surface of bluff bodies in turbulent boundary layers: evaluation of a forced-convective temperature wall function for mixed convection. J. Wind Eng. Ind. Aerodyn. 104-106: 439-446.
92. Blocken B, Carmeliet J. 2006. The influence of the wind-blocking effect by a building on its wind-driven rain exposure. J. Wind Eng. Ind. Aerodyn. 94(2): 101-127.
93. Blocken B, Moonen P, Stathopoulos T, Carmeliet J. 2008. A numerical study on the existence of the Venturi-effect in passages between perpendicular buildings. J. Eng. Mech. 134(12): 1021-1028.
94. Blocken B, Stathopoulos T, Carmeliet J. 2008. Wind environmental conditions in passages between two long narrow perpendicular buildings. J. Aerosp. Eng. 21(4): 280-287.
95. Blocken B, van Hooff T, Aanen L, Bronsema B. 2011. Computational analysis of the performance of a venturi-shaped roof for natural ventilation: venturi-effect versus wind-blocking effect. Comput. Fluids 48(1): 202-213.
96. Venturi GB. 1799. Experimental enquiries concerning the principle of the lateral communication of motion in fluids: applied to the explanation of various hydraulic phenomena. Translated from the French by Nicholson W, 1st English ed., J. Taylor, Architectural Library, High-Holborn, London.
97. Gandemer J. 1975. Wind environment around buildings: aerodynamic concepts. Proc. 4th Int. Conf. Wind Effects on Buildings and Structures, Heathrow 1975, Cambridge University Press, 423-432.
98. Dutt AJ. 1991. Wind flow in an urban environment. Environ. Monit. Assess. 19(1-3): 495-506.
99. Stathopoulos T, Lazure L, Saathoff P, Gupta A. 2004. The effect of stack height, stack location and roof-top structures on air intake contamination - A laboratory and full-scale study. IRSST report R-392, Montreal, Canada, 2004.
100. Bronsema B. 2005. Earth, Wind & Fire – Towards new concepts for climate control in buildings. CIB W096 Meeting Lyngby, November 2-4, 2005.
101. Bronsema B. 2010. Earth, wind & fire; air-conditioning powered by nature. 10th REHVA World Congress. Antalya, Turkey: CLIMA, 9-12 May 2010.
102. Oke TR. 1973. City size and the urban heat island. Atmos. Environ. 7: 769–779.
103. Oke TR. 1976. The distinction between canopy and boundary layer urban heat islands. Atmosphere 14: 269–277.
104. Steenveld GJ, Koopmans S, Heusinkveld BG, van Hove LWA, Holtslag AAM. 2011. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. J. Geophys. Res. 116: D20129.

Curriculum vitae

Prof. Bert Blocken was appointed full-time professor in Building Physics at the Department of the Built Environment at Eindhoven University of Technology (TU/e) on April 1, 2011.

Bert Blocken (1974) is an MSc graduate (1998) from Leuven University in Belgium where he gained his PhD in Civil Engineering (2004). In 2004, he was awarded the Postdoctoral Fellowship of the Fund for Scientific Research in Flanders (FWO-Vlaanderen), one year of which he spent at Concordia University in Montreal. In June 2006, he was appointed assistant professor at the Department of the Built Environment at TU/e. In January 2009, he was appointed associate professor and in April 2011 full professor and Chair of Building Physics at the same department and university.
His main area of expertise is Urban Physics. He has published 75 papers in international peer-reviewed journals and 140 papers in international conference proceedings. He currently supervises a team of 13 PhD students and 11 MSc students. He has received several awards, including six best-paper awards over the past 3 years from the leading journal *Building and Environment* and at international conferences, a top-cited author award from the leading journal *Atmospheric Environment* and the 2011 best-lecturer award from the third-year Bachelor's students at the Department of the Built Environment. He is also a guest lecturer at ETH Zurich and at the von Karman Institute for Fluid Dynamics.

Colophon

Production
Communicatie Expertise Centrum TU/e

Cover photography
Rob Stork, Eindhoven

Design
Grefo Prepress, Sint-Oedenrode

Print
Drukkerij Snep, Eindhoven

ISBN 978-90-386-3250-6
NUR 955

Digital version:
www.tue.nl/bib/

Visiting address
Den Dolech 2
5612 AZ Eindhoven
The Netherlands

Postal address
P.O.Box 513
5600 MB Eindhoven
The Netherlands

Tel. +31 40 247 91 11
www.tue.nl

Technische Universiteit
Eindhoven
University of Technology