A new wind direction-driven heat convection model is needed in dynamic simulation: what, why, and how

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Abstract

Wind plays an essential role in the heat convection on building outside surfaces. In EnergyPlus, a dynamic simulation program, heat convection models present several limitations reported by the scientific community. However, this communication reveals and discusses some implications that highlight the importance of developing more accurate models. The current models are first analyzed to identify what are the pitfalls considering the influence of wind direction on the thermal performance of the building walls. Then, a discussion is made on why their implications are important and, lastly, it is suggested how wind direction-driven studies and new models can overcome this issue. Concluding, this communication calls for efforts from the scientific community to research and develop more accurate models for wind-driven surface convection.

Keywords: outside heat convection coefficient, wind direction, building performance simulation, EnergyPlus

1 Introduction

Wind affects the building's thermal performance in different ways. It creates an air pressure difference leading to air exchanges between the inside and outside environment and affects the convective heat flux by enhancing the convection heat transfer rate on the outside surface of the building envelope. Both effects are considered in building performance simulation programs. In the latter case, the currently available models in EnergyPlus[1] for vertical surfaces present several pitfalls that require specific attention. These issues were reported by the scientific community [1,2]. However, more profound implications of these issues were unknown, which this communication unveils and discusses, showing some amount of noise error in the heat flux calculation.

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[1] At the date of the submission of this communication (October 2021) the most recent EnergyPlus version was 9.6.0.

To grasp the implication of these issues, we need to comprehend how the outside surface heat balance is determined in EnergyPlus. The heat balance algorithm considers short and long wavelength radiation, conduction, and convective heat fluxes in its calculations. The rate of heat transfer by convection at the outer surface is modeled using the classical formulation $\dot{Q}_c = h_c A(T_s - T_a)$, where h_c represents the exterior convection coefficient, which is split into the forced (h_f) and natural (h_n) components ($h_c = h_f + h_n$) [3].

To compute h_c, EnergyPlus presents the following main models for opaque vertical elements: Simple Combined, TARP, MoWiTT, DOE-2, and Adaptive Convection Algorithm. However, *a)* the Simple Combined model is entirely invariant to wind direction; *b)* in the DOE-2, TARP, and MoWITT models, the convection heat transfer coefficient (h_c) does not consider the wind direction angle, and the surfaces are only classified as either windward[2] or leeward, while flow structures on the side facades are very different [5]; and *c)* in the Adaptive Convection Algorithm, which activates user-selected models depending on the surface to be windward or leeward, only some of the available models calculate h_f for different wind direction angles, however just for specific intervals.

The Adaptive Convection Algorithm allows specifying the convection model according to the surface type. In this algorithm, the h_c equation is split into two parts, and there are separate model equation selections for forced convection (h_f) and natural convection (h_n) [3]. The former is the key for this discussion since wind direction influences the forced convection component exclusively. Therefore, the wind-driven models available for h_f within the Adaptive Convection Algorithm may be divided into the ones that are: *a)* invariant with wind direction – Nusselt-Jurges, McAdams, and Mitchell –; *b)* sensitive only to windward or leeward orientations – TARP, MoWiTT, and DOE-2 –; and c) sensitive to the wind direction angle – Blocken-Windward and Emmel-Vertical. A summary of the available models and their equations is presented in Table 1.

1.1 Models invariant to wind direction

The Simple Combined model is a simple second-degree polynomial proposed by ASHRAE [6], using surface roughness and local surface windspeed to calculate the exterior heat transfer coefficient. It is, however, entirely

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[2] A surface is classified as windward if the angle of incidence between the normal to the surface and the wind direction is less than ±90°, and leeward for all other directions [4].

invariant with wind direction. This simple correlation yields a combined convection and radiation heat transfer coefficient, while all other algorithms yield a convection-only heat transfer coefficient.

The Nusselt-Jurges, McAdams, and Mitchell wind-driven convection models are not sensitive to wind direction or surface roughness, being uniquely dependent on the wind velocity [7-9]. In addition, the Mitchell algorithm uses a geometric scale based on the building volume.

1.2 Models based on leeward and windward surface's orientation

The Thermal Analysis Research Program (TARP) algorithm combines natural and wind-driven convection correlations from laboratory measurements on flat plates. The forced convection component is sensitive to surface roughness, wind speed, surface size, and wind exposition (windward or leeward), based on the more detailed algorithm of Sparrow *et al*. [10]. As for the natural convection component, the model correlates the convective heat transfer coefficient to the surface orientation and the difference between the outside surface and air temperatures.

The MoWiTT model is based on measurements taken at the Mobile Window Thermal Test (MoWiTT) facility [11]. The correlation applies to very smooth, vertical surfaces (*e.g.*, window glass) and, therefore, is most appropriate for windows. It mainly depends on the wind exposition (windward or leeward), wind speed, and temperature difference between the surface and outside air [11,12].

The DOE-2 model uses a correlation from measurements for rough surfaces. It combines the MoWiTT and BLAST Detailed (similar to the TARP) convection models [13].

1.3 Models sensitive to wind direction

The Blocken-Windward model consists of a set of correlations for h_f for windward-facing outdoor surfaces [14]. These correlations depend on the air velocity and wind direction in four equal angle intervals ranging between 0° and 100°. However, this model applies only to windward surfaces and lacks a natural convection component. Therefore, it must be combined with other models in the Adaptive Convection Algorithm to cover the remaining cases.

The Emmel-Vertical model consists of a set of correlations for h_f for outdoor vertical surfaces [15]. As in the Blocken-Windward model, these correlations depend on the air velocity at the location for different wind direction angles, considering, in this case, five intervals between 0° and 180°. Although covering all wind directions, this model lacks the natural convection component. Moreover, the model was developed for simple parallelepiped-shaped low-rise buildings.

Table 1 – List of convection heat transfer coefficient models available in EnergyPlus [3].

Model	Equation	References
Simple Combined	$h_c = D + EV_z + FV_z^2$ (1)	[6]
TARP	$h_f = 2.537\, W_f R_f \left(\frac{PV_z}{A}\right)^{1/2}$ (2) $h_n = 1.31\, \lvert\Delta T\rvert^{\frac{1}{3}}$ (3)	[10,16,17]
MoWiTT	$h_c = \sqrt{\left[C_t(\Delta T)^{\frac{1}{3}}\right]^2 + (aV_z^b)^2}$ (4)	[11,12]
DOE-2	$h_c = \left[C_t(\Delta T)^{\frac{1}{3}}\right]^2 + h_{n,\mathrm{TARP}}$ (5)	[13]
Blocken-Windward	$h_f = 4.6\, V_{10\mathrm{m}}^{0.89}, \quad \theta \leq 11.25$ (6) $h_f = 5.0\, V_{10\mathrm{m}}^{0.80}, \quad 11.25 < \theta \leq 33.75$ (7) $h_f = 4.6\, V_{10\mathrm{m}}^{0.84}, \quad 33.75 < \theta \leq 56.25$ (8) $h_f = 4.5\, V_{10\mathrm{m}}^{0.81}, \quad 56.25 < \theta \leq 100$ (9)	[14]
Emmel-Vertical	$h_f = 5.14\, V_{10\mathrm{m}}^{0.81}, \quad \theta \leq 22.5$ (10) $h_f = 3.34\, V_{10\mathrm{m}}^{0.84}, \quad 22.5 < \theta \leq 67.5$ (11) $h_f = 4.78\, V_{10\mathrm{m}}^{0.71}, \quad 67.5 < \theta \leq 112.5$ (12) $h_f = 4.05\, V_{10\mathrm{m}}^{0.77}, \quad 112.5 < \theta \leq 157.5$ (13) $h_f = 3.54\, V_{10\mathrm{m}}^{0.76}, \quad 157.5 < \theta \leq 180.0$ (14)	[15]
Nusselt-Jurges	$h_c = 5.8 + 3.94\, V_z$ (15)	[1,7]
McAdams	$h_c = 5.7 + 3.8\, V_z$ (16)	[1,8]
Mitchell	$h_f = \frac{8.6\, V_z^{0.6}}{L^{0.4}}$ (17)	[1,9]

2 What is the problem?

Most of the implemented models present significant limitations. One of those limitations is not considering the actual angle of the wind direction (TARP, MoWiTT, and DOE-2). Some models are even entirely invariant for wind direction (Simple Combined, Nusselt-Jurges, McAdams, and Mitchel). Only the Blocken and Emmel models estimate h_f accounting for the wind direction angles, and yet, just for specific intervals. In both cases, the natural convection component is lacking. The difference between them is that the Blocken model applies only to windward surfaces, while the Emmel model was developed for simple parallelepiped-shaped low-rise buildings. Moreover, only the TARP model (and the Mitchel, to some extent) considers the facade size by including the surface perimeter and area, but mainly from the perspective of boundary layer development over a flat plate [16]. The user can also define custom models in EnergyPlus; nevertheless, these refer to performance curves of h_f as a function of wind speed, applicable just to windward or leeward surfaces, thus not considering the wind direction angle. Table 2 presents a summary of the models' limitations. It must be noticed that there are numerous other mature models available in the literature and other building simulation programs; however, they present similar issues [1,2,18].

Table 2 – Summary of the models' limitations.

Model	**Wind-related limitations**	**Other limitations**	
Simple Combined	Invariant to wind direction[a]	Do not consider the building or surface size	
Nusselt-Jurges			
McAdams			
Mitchell			
TARP	Insensitive to the wind direction angle[b]		
MoWiTT		More appropriate for windows	Do not consider the building or surface size
DOE-2			
Blocken-Windward	Divided into specific intervals of wind direction angle	Applicable only to windward surfaces	
Emmel-Vertical		Developed for simple, rectangular low-rise buildings	

[a] Does not consider the wind direction in any form.

[b] Considers the wind direction only as windward or leeward surface orientations, not considering the wind direction angle.

As presented above, most of the available models are applied according to the windward-leeward transition. However, this presents several limitations. One of them occurs when a building has its lateral walls aligned with the wind direction. Thus, assuming a regular building with four facades, three out of the four walls are considered windward, resulting in the same h_c value. Therefore, a slight variation of the wind direction results in a significant, unrealistic variation in HVAC energy demand when performing a dynamic thermal simulation of the building.

For instance, imagine a building with a rectangular footprint with one of its smaller facades facing a North wind (Figure 1). In this case, three facades are considered windward (same h_c). However, a mere one-degree change in the wind direction leads to only having two windward facades. When the wind reaches 90°, the building will again have three facades windward. Therefore, the passage from windward to leeward without correctly considering the effect of the wind direction angle leads to considerably different h_c values, and thus significant HVAC energy requirement differences. Only the Blocken and Emmel models consider the wind direction angle. However, given their limitations, they are also not the most adequate.

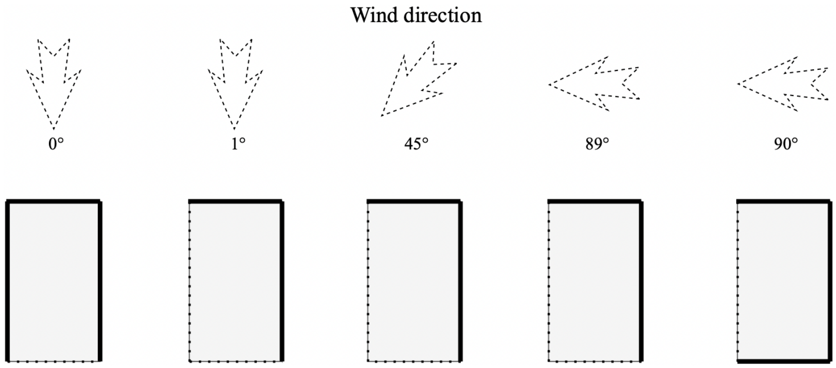


Figure 1 – Effect of the wind direction on the number of windward surfaces (depicted in continuous strong lines).

The abovementioned limitations may translate into problems regarding the implementation and realism of the simulation models. For example, Figure 2 presents a set of results regarding a simple parallelepiped-shaped building in Lisbon, Portugal (local weather data obtained from climate.onebuilding.org [19]), using three exterior surface convection models (Simple Combined, TARP, and Emmel). The annual HVAC energy consumption values (heating plus cooling, for a constant annual HVAC setpoint of 22 °C) are presented for different building orientations, covering a 360° orientation span calculated in steps of one degree (the input data file is available as supplementary material). Besides having distinguishable curves, the range of the energy performance is also different in each model, thus indicating a varying range of accuracy.

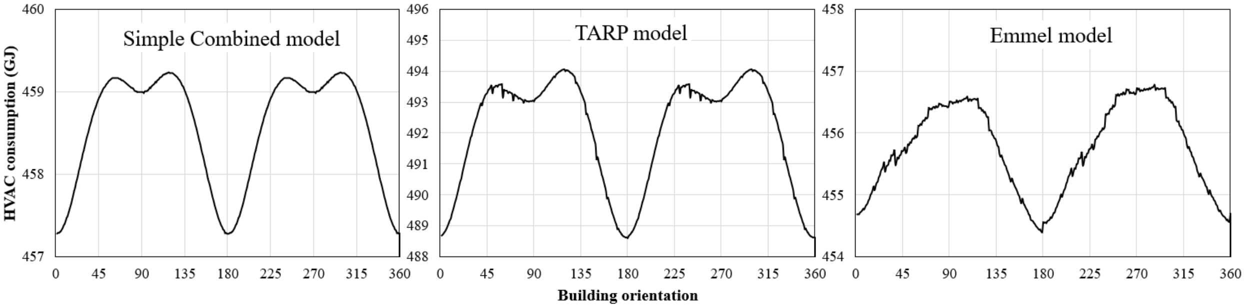
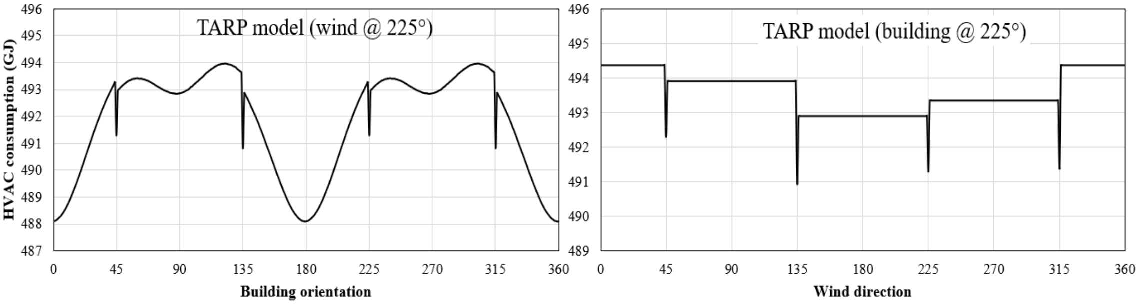


Figure 2 – Building annual HVAC consumption for different orientations, applying the Simple Combined, TARP, and Emmel models.

As referred above, the Simple Combined model is invariant with wind direction, thus presenting a smooth curve for the energy consumption. However, for both the TARP and Emmel models, the curve presents a set of downward spikes (particularly in the Emmel model). In the TARP model case, these spikes are due to the windward-leeward transitions. This effect can be demonstrated by fixing, for instance, the wind direction at 225° (southwest) and carrying out the same analysis. The spikes are noticeable at each 90° transition, starting at 45° (Figure 3a). In other words, every time one of the walls has the azimuth towards the wind direction, the windward-leeward transition issue occurs (spike). Also noticeable are the odd curve discontinuities before and after each spike.



a) b)

Figure 3 – Building annual HVAC consumption for different orientations with (a) fixed wind direction and (b) fixed building position, applying the TARP model.

In addition, the issue can also be demonstrated by fixing the building azimuth (at 225°) and plotting the annual HVAC energy consumption for all 360°-span wind directions (*i.e.*, for each angle, the wind direction is considered constant at the respective value throughout the entire annual simulation). The results are presented in Figure 3b. They illustrate not only the transition spikes, again at 45°, 135°, 225° and 315° (*i.e.*, at each 90° starting at 45°), but also presents a stepped shape between those values when two of the facades are windward (90° step width). The model considers three facades windward at those four precise directions, thus producing a sharp variation in HVAC energy consumption compared to the preceding and subsequent wind direction angles. It can also be noticed that by not considering the wind direction angle in the TARP model (beyond the windward-leeward transition), the energy consumption remains constant between those spikes, presenting abrupt changes at each transition (explaining the odd curve discontinuities in Figure 3a). This stepped behavior means that, even though the wind is striking the surfaces at a different angle that reaches almost a perpendicular direction, the energy performance of the building remains the same.

The irregular behavior is much more noticeable for the Emmel than for the TARP model, with even higher discontinuities. This behavior is depicted in Figure 4a, in which the wind direction is fixed at 225°. Because this model considers a set of intervals of wind direction angles, covering a 180° range, for the h_f calculation (Table **1**), and not the orientation of the wall being windward or leeward, the wind direction angle intervals result in abrupt transitions between the model's specific angle intervals. The stepped behavior can also be noticed by fixing the building azimuth and assessing the effect of the different wind directions (covering the 360°-span), as presented in Figure 4b. The abrupt transitions occur in the limits of the angle range, while the energy consumption remains constant between them, as observed for the TARP model, however, in smaller steps (due to the specific angle intervals).

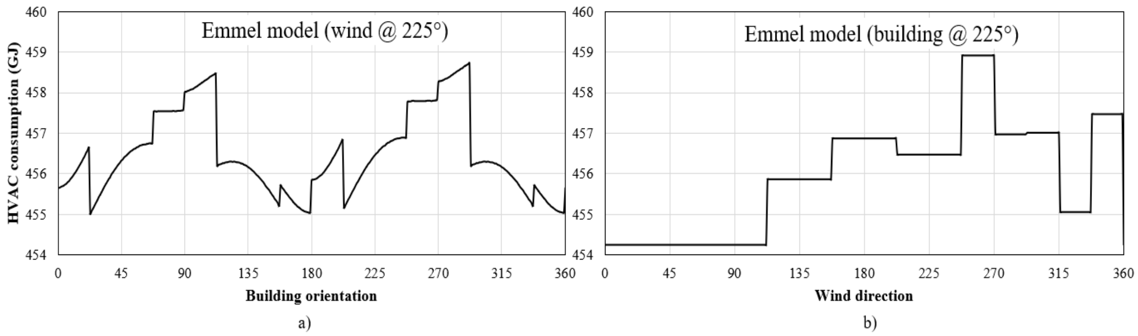


Figure 4 – Building annual HVAC consumption for different orientations with (a) fixed wind direction and (b) fixed building position, applying the Emmel model.

Continuing on Figure 4b, and contrarily to what was expected, no angle range transitions occur for wind directions between 0° and 112.5°. This aspect led us to unveil an implementation error of the Emmel model in the EnergyPlus code – the angle between the wind direction and surface azimuth is incorrectly determined (as reported to EnergyPlus developers in issue #9106). As such, the most detailed model available does not yield reliable results (although the abovementioned conclusions are still valid, in general). Thus, the use of this model is not recommended before these issues are resolved.

The issues in the exterior convection models can be summarized as follows: (i) the wind direction angle is not properly considered (resulting in spiked and stepped behaviors) or not considered at all, thus producing different levels of accuracy, (ii) the models are limited to specific conditions (*e.g.*, building and surface type, and facade orientation), and (iii) most models do not consider the building size.

3 Why is this important?

Although the examples above depict what seems small spikes in the total energy consumption, the fact is that this causes great discrepancies in the heat transfer calculation in the building surfaces. In addition, the issue is more evident in windy and sunny climates or where wind strikes the building from a prevailing direction, thus producing a significant whole-year cumulative impact. Also, the building geometry, such as facades areas or building size, and the location characteristics, such as terrain type and elevation, contribute to increasing the magnitude of those errors.

EnergyPlus offers a set of outside convection algorithms, which allows the user to choose the most suitable form offered by the program, given the lack of generality of the existing forced convection coefficient correlations (as discussed by Palyvos back in 2008 [1] – still one of the main references for EnergyPlus). However, that choice must be made carefully since the modeler should refer to the original works to assess the applicability to the problem at hand. Moreover, as discussed above, the available algorithms may not be totally adequate. In this sense, this requirement limits the software's user-friendliness or can defraud the user's expectation in using models that accurately capture the physical phenomenon. As these simulation tools evolve, they increase in features and grow in complexity, thus becoming harder and harder for a regular modeler to consider all the shortfalls of every single model.

The expectation of the user should not be downplayed. EnergyPlus is a common software used worldwide by numerous researchers and building professionals. Some combine it with optimization algorithms to find optimum design solutions from a set of variables. One of those variables is precisely the building orientation, which is directly involved by the reported issues above. These issues may translate into small errors with large overall consequences, such as when a search algorithm (*e.g.*, gradient-descent algorithms) is trapped in an erroneous local minimum. This situation is particularly worrisome in an early design stage when the most important decisions are made.

Furthermore, although dynamic simulation requires a whole set of simplifications, less accomplished mathematical models and implementations of a particular physical phenomenon seriously hamper the models' calibration and validation. For instance, the stepped behavior that results from the discretization of wind effect by angle intervals, described above, means that the solution space of the building orientation variable has itself a varying noise error depending on the selected value that induces error in calibration and validation.

4 How is this a scientific problem?

The lack of generality of the existing wind convection coefficient correlations presents a challenge for future research. Given the number of variables to consider, it is extremely unlikely to develop a single general model. However, since these models can be applied in building performance assessments, correlations with standard building typologies should be defined and more complete models are needed, considering the effect of the wind direction angle (without producing abrupt h_f variations, and thus energy consumption unrealistic variations).

The development of new models is not solely a coding task. It is, above all, a scientific problem, which requires scientific methods to study, develop, and validate new approaches. One of the objectives should be to avoid the spiked and stepped behavior presented above by having a higher level of discretization of the angles or developing a formulation that calculates a continuous variation of h_f to produce a smooth transition as the wind direction changes. Also, the accuracy of the models is of capital importance, given its effect on simulation output to assess the building energy performance. The solution should also consider the combined effect of the whole group of polyhedron surfaces that define the building.

Recent studies have sought to address some of the issues [20,23] and several research paths may be pursued. For instance, developing new field measurements, analyzing physical scale models (wind tunnel measurements), and using computational techniques, such as computational fluid dynamics, would prove of great importance. In this way, a much smaller set of realistic, well-proven, and generally accepted correlations may be developed, which would greatly help the modeler. For instance, computational fluid dynamics, validated against wind-tunnel experiments, can be extended by considering specific local conditions [20,21], and expressions for forced convective heat transfer coefficients can be generalized [5,22,23]. Also, full-scale measurements on building facades may be performed [24–26], despite not being currently a generalized method.

The implementation of future models should also consider inclined surfaces besides upright vertical walls since the wind effect on those inclined surfaces can be very different from the vertical ones. In addition, it would also help to generate models that would consider roofs and other non-wall surfaces.

Therefore, we call for the scientific community to accept the challenge of developing a more robust and accurate model to be implemented in EnergyPlus. The model can also be helpful to other building simulation programs where this issue may occur.

Symbols

a – Wind direction-dependent coefficients

A – Surface area

b – Wind direction-dependent coefficients

C_t – Turbulent natural convection constant

D – Material roughness coefficient

E – Material roughness coefficient

F – Material roughness coefficient

h_c – Exterior convection coefficient

h_f – Forced convection coefficient

h_n – Natural convection coefficient

L – Cube root of the building's total volume

$\dot{Q}_c$ – Rate of exterior convective heat transfer

R_f – Surface roughness multiplier

T_a – Outdoor air temperature

T_s – Surface temperature

$V_{10\mathrm{m}}$ – Air velocity at the location of the weather station

V_z – Local wind speed calculated at the height above ground of the surface centroid

W_f – Leeward/windward coefficient

ΔT – Difference between surface and zone air temperatures ($\Delta T = T_a - T_s$)

θ – Angle of incidence between the wind and the surface in degrees

Σ – Surface tilt angle

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