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An overview of simulation tools for predicting the mean radiant temperature in an outdoor space

Emanuele Naboni[a,b]*, Marco Meloni[a], Silvia Coccolo[b], Jérôme Kaempf[b,c], Jean-Louis Scartezzini[b]*

[a]The Royal Danish Academy of Fine Arts, School of Architecture, Design & Conservation KADK, Philip de Langes Allé 10, 1425 Copenhagen, Denmark

[b]EPFL Solar Energy and Building Physics Laboratory (LESO-PB), Station 18, 1015 Lausanne, Switzerland

[c]School of Engineering and Architecture of Fribourg, Institute for Applied Research into Energy Systems (ENERGY), Bd de Pérolles 80 - CP 32, 1705 Fribourg, Switzerland

Abstract

When modelling outdoor microclimates, researchers and designers need to be aware of the modelling capabilities and limitations of tools. This comparative study attempts to understand how tools such as CitySim Pro, ENVI-met, RayMan, Grasshopper plug-ins Honeybee / Ladybug and Autodesk CFD, evaluate the Mean Radiant Temperature (MRT), one of the main parameters governing human energy balance. To this purpose, the space underneath and surrounding the Rolex Learning Center, located on the EPFL campus in Lausanne, were modelled. Significant variations of MRT predictions were recorded. This led to the review of the physical modelling assumptions that each of the calculation engines operates. Based on the tools' available documentation, answers to forums, interviews with the developers, and tool codes, the paper lists how all the variables that affect MRT are considered. Although not exhaustively, the paper lists the main differences among tools, leading to the understanding of the types of physical context that they could simulate.

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Keywords: Outdoor Simulation Tools; Outdoor Comfort Simulation; Human Comfort; Mean Radiant Temperature

* Corresponding author. *E-mail address:* emanuele.naboni@kadk.dk

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1. Introduction

In the last decade, the scientific community has become interested in how urban design impacts outdoor thermal comfort. Enhancing the health and well-being of citizens, reducing heat and cold stress, and prolonging periods of comfort, are new focuses in design (1). For instance, it is today being investigated how the built environment alters local microclimates by influencing a series of thermodynamic phenomena (2,3,4). However, because of the dynamic nature of the urban environment, it is difficult to find a simulation tool that adequately models all of the physical context types (5). Considering that in the last five years, researchers and designers have increasingly approached the modelling of microclimates (6), being aware of the modelling capabilities, and limitations of tools applicability has becomed critical.

When limiting the discourse to Outdoor Comfort Simulation tools (OCS), it is key to understand how the Mean Radiant Temperature (MRT) is modelled. This is one of the important meteorological parameters governing human energy balance and thermal comfort (7). It is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (8). MRT is often proposed as a better metric than air temperature or apparent temperature to analyze the impact of climate on people's health (9). It is also considered a "spatial metric": when compared to other variables influencing thermal comfort, MRT shows larger spatial variation over short distances (10,11). Finally, MRT is the basis of several Outdoor Comfort Indexes.

In the last three years, several practice-oriented tools have been developed and refined to include MRT modelling. This study compares OCS tools that are based on 3D models: CitySim Pro, ENVI-met V.4, RayMan 1.2, Grasshopper plug-ins Honeybee 0.0.60 and Ladybug 0.0.63, and Autodesk CFD 2016. Tools were tested in "action" when predicting the MRT of key points in and around the Rolex Building Center at the EPFL campus. It was noticed that tools' MRT calculation could strongly differ, thus calling for further investigations. Scarce or no information is available on how the tools calculate MRT (12). Based on the tools' available documentation, answers to forums, interviews with the developers, and tool codes, the paper lists how all the variables that impact MRT are considered. Although not exhaustively, the paper lists the main differences among tools, leading to the understanding of what type of physical context each can simulate.

2. MRT Prediction diverge among tools

The Rolex Learning Center, located on the EPFL campus in Lausanne (Switzerland), is chosen as a case study. The outdoor space is partially covered by buildings and suitable for comfort analysis. MRT calculations are performed for a series of typical microclimatic conditions (e.g. sun-lighted/shaded, the wind exposed/protected, etc.) at six chosen points (Figure 1) located at 1.1 meters above ground to represent the center of gravity of a pedestrian standing outside. A geometrical model is created with Rhinoceros (13). A typical meteorological year (TMY) profile is generated with Meteonorm (14). The hottest time of the year (19th of August at 15:00) and the coldest (12th of January at 10:00) are simulated. The hottest time has a dry bulb temperature (DBT) of 26.1 °C and relative humidity (RH) of 55%. The coldest time has a DBT of -6°C, and an RH of 94%. Models are created with each of the above-mentioned tools.

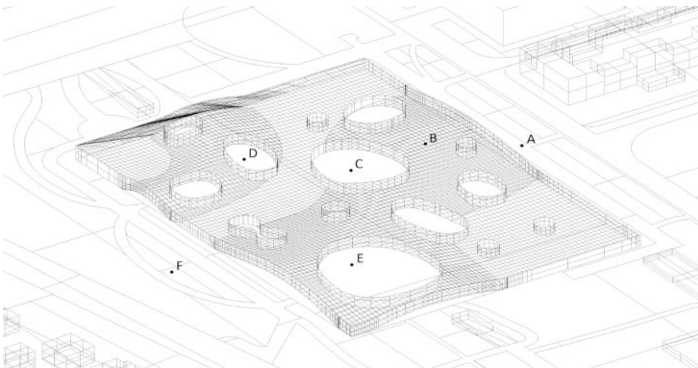

Fig. 1. Location of MRT point of analysis underneath and around the Rolex Learning Center.

3. Results

MRT predictions for the 6 selected points are presented in Tables 1 and 2. Most of the input values are simulated with validated tools. The Sky View Factor is calculated with the Ladybug Raytracing component, the Shortwave radiation with Radiance (via DIVA), local Airflows are computed with Ansys, local Air Temperature and Humidity are calculated with ENVI-met. MRT outputs calculated for different points are listed under the outputs and conveyed in the graphs in Figure 2. MRT curves in winter are included within the ranges of -7 and +3, with the exception of Honeybee and Ladybug curve. In summer, when radiation exchange increases, MRT prediction differences amplifies, thus calling for a closer look into the modelling assumptions operated by each of the tools. To gain a full understanding of how tools predict MRT, it could be necessary to collect on-site measurements and compare simulation outputs. However, the limited scope of the research is to review inputs and equations, weighting capabilities and limitation of applicability of tools, at their current stage of development.

Table 1: MRT results in summer scenario, 19th August at 15:00

Input								Output				
Date: 19 August Time: 15:00	**Albedo (-)**	**Sky View Factor (%)**	**Sky Exposure (%)**	**Shortwave radiation (kWh/m²)**	**Local Wind speed (m/s)**	**Local Air temperature (°C)**	**Local Relative humidity (%)**	**CitySim Pro MRT (°C)**	**ENVI-met MRT (°C)**	**RayMan MRT (°C)**	**HoneyBee and Ladybug MRT (°C)**	**Autodesk CFD MRT (°C)**
Point A	0.17	90	74	1,42	0,14	31.19	45.04	53.53	67.86	51.5	41.12	54.19
Point B	0.20	0	1	0	0,17	30.77	44.7	41.87	32.78	38.7	26.32	52.91
Point C	0.20	89	69	1,42	0,11	30.7	44	51.16	68.08	50.5	40.5	62.31
Point D	0.20	80	57	0,18	0,09	30.63	44.6	42.28	65.27	50.8	34.02	61.46
Point E	0.20	76	57	1,07	0,18	30.37	44.36	48.30	66.84	42.6	35.12	66.2
Point F	0.25	98	90	1,60	0,25	30.45	46.15	56.60	68.47	51.5	41.65	54.75

Table 2: MRT results in winter scenario, 12th January at 10:00

Input								Output				
Date: 12 January Time: 10:00	**Albedo (-)**	**Sky View Factor (%)**	**Sky Exposure (%)**	**Shortwave radiation (kWh/m²)**	**Local Wind speed (m/s)**	**Local Air temperature (°C)**	**Local Relative humidity (%)**	**CitySim Pro MRT (°C)**	**ENVI-met MRT (°C)**	**RayMan MRT (°C)**	**HoneyBee and Ladybug MRT (°C)**	**Autodesk CFD MRT (°C)**
Point A	0.17	90	74	0,06	0,17	-3.1	100	-1.79	-4.26	2.9	11.55	-1.17
Point B	0.20	0	1	0	0,1	-1.34	90.9	-2.53	-6.58	-1.3	12.08	-0.51
Point C	0.20	89	69	0,03	0,13	-2.99	100	-5.32	-4.08	2.8	11.73	-2.05
Point D	0.20	80	57	0	0.01	-2.39	96.6	-6.62	-5.97	2.9	11.99	-5
Point E	0.20	76	57	0,06	0.01	-2.5	100	-3.11	-4.59	2.5	11.85	-2.01
Point F	0.25	98	90	0,11	0,26	-2.69	100	1.22	-3.15	2.9	11.53	-3.77

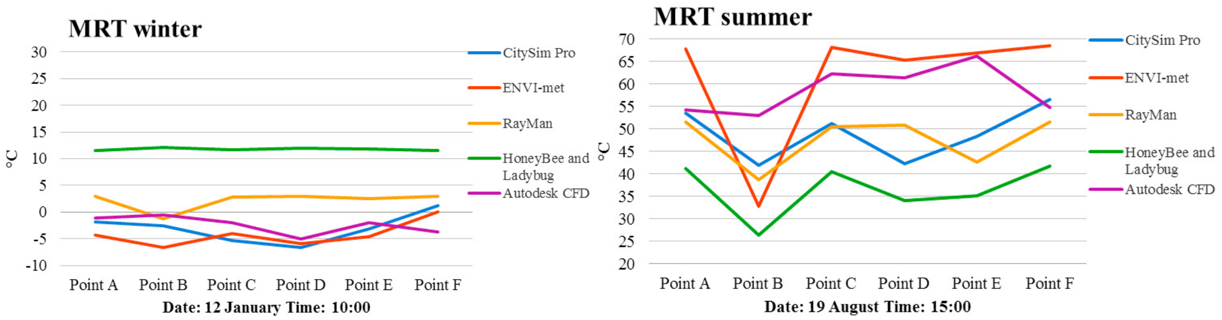

Figure 2. Graphs of MRT results in winter and summer scenario

4. Tools Outdoor Mean Radiant Temperature Equations

A preliminary review of what the tools account for when predicting MRT is proposed in Table 3. The table is organized according to the factors that influence MRT predictions at the centre point of a human body: the human body radiation exchanges, the shortwave radiation, the longwave radiation, the local wind profile, the sky and surfaces View Factors. It is described how different tools model these factors and with what assumptions.

Table 3. Variables that are considered by tools in their MRT calculations and distinction of input data (I) and calculated data (C)

	CitySim Pro	ENVI-met	RayMan	Honeybee and Ladybug	Autodesk CFD
Human Body Radiation Exchange					
Shape/Position	Accounted (I)	Simplified (I)	Simplified (I)	Accounted (I)	Simplified (I)
Shortwave absorption	Accounted (I)	Accounted (I)	Accounted (I)	Accounted (I)	Accounted (I)
Longwave emissivity	Accounted (I)	Accounted (I)	Accounted (I)	Accounted (I)	Accounted (I)
Shortwave Radiation Exchange					
Direct radiation	Accounted (C)	Accounted (C)	Simplified (I)	Accounted (C)	Accounted (C)
Diffuse sky radiation	Accounted (C)	Accounted (C)	Simplified (I)	Accounted (C)	Simplified (C)
Diffuse reflected radiation (Buildings)	Accounted (C)	Accounted (C)	Not accounted	Accounted (C)	Not Accounted
Diffuse reflected radiation (Free standing objects)	Accounted (C)	Accounted (C)	Not accounted	Accounted (C)	Not Accounted
Diffuse reflected radiation (Vegetation)	Accounted (C)	Accounted (C)	Not accounted	Simplified (C)	Not Accounted
Diffuse reflected radiation (Ground)	Accounted (C)	Accounted (C)	Accounted (C)	Accounted (C)	Not Accounted
Sky view factor	Deterministically (C)	Deterministically (C)	Fish-eye photo (I)	Ray Tracing (C)	Deterministically (C)
Surface view factor	Deterministically (C)	Deterministically (C)	Fish-eye photo (I)	Ray Tracing (C)	Deterministically (C)
Longwave Radiation Exchange					
Longwave radiation exchange with the sky	Accounted (C)	Accounted (C)	Accounted (C)	Accounted (C)	Not Accounted
Longwave radiation (Buildings)	Accounted (C)	Simplified (C)	Not accounted	Simplified (C)	Simplified (C)
Longwave radiation (Free standing objects)	Not accounted	Simplified (C)	Not accounted	Not accounted	Accounted (C)
Longwave radiation (Vegetation)	Accounted (C)	Accounted (C)	Not accounted	Not accounted	Not accounted
Longwave radiation (Ground)	Accounted (C)	Accounted (C)	Simplified (C)	Simplified (C)	Simplified (C)
(Transpiration (Vegetation)	Accounted (C)	Accounted (C)	Not accounted	Not accounted	Not accounted
Evaporation (Ground)	Accounted (C)	Accounted (C)	Simplified (I)	Not accounted	Not Accounted
Local Wind Speed	Not accounted	Accounted (C)	Not accounted	Not accounted	Accounted (C)
Local Wind Direction	Not accounted	Accounted (C)	Not accounted	Not accounted	Accounted (C)
Sky view factor	Deterministically (C)	Deterministically (C)	Fish-eye photo (I)	Ray Tracing (C)	Deterministically (C)
Surface view factor	Deterministically (C)	Deterministically (C)	Fish-eye photo (I)	Ray Tracing (C)	Deterministically (C)

CitySim Pro (15) predicts energy fluxes at various scales. It is validated according to the Building Energy Simulation Test (BESTEST), as well as against EnergyPlus (16). MRT calculation is based on the integral radiation measurement defined by Hoppe (17). The human body shape and position, shortwave coefficient absorption and longwave emissivity are definable. Surface and sky view factors are calculated with a deterministic method. Complex 3D surfaces and building temperatures are estimated based on radiation exchanges and operation profiles. The model considers the evaporation of the ground and the transpiration of vegetation entities (18,19). ENVI-met simulates the surface-plant-air interactions in an urban environment (20). It is validated and compared against onsite measurements (21,22,23). ENVI-met MRT is defined by the equation of Bruse (24), derived from Fanger (25). The human body is outlined by default values. The temperature of each building surface viewed from the face of a target point is assessed as a weighted temperature. ENVI-met does not use a deterministic View Factor. However, the new release V4.1.1 introduced the more accurate Indexed View Sphere (IVS). ENVI-met considers buildings temperatures in a simplified way. Ground evaporation and vegetations transpiration are fully calculated. RayMan is a human-biometeorological tool based on radiant flux and thermophysiological indices (26). Outputs are validated against on-site measurements (27). The MRT calculation is based on Hoppe. The human body is defined by default values. The model uses a Fish-eye photo method to calculate Sky and Surface View Factors. RayMan simplifies longwave radiation exchanges from ground, buildings, vegetation and freestanding objects by the means of a simplified shading mask. Honeybee and Ladybug (28) are plugins for Grasshopper (29, 30). They simulate MRT by computing a long-wave MRT based on surface temperatures received from EnergyPlus and factored byView Factors studied with Raytracing (31). The sky temperature adjusts the MRT value. The long-wave MRT is modified to consider shortwaves with the SolarCal model (32). The longwave radiation exchange with the sky is based on the Man-Environment Heat Exchange Model 2005 (33) (34). The human body is defined by shortwave absorption and longwave emission default values. The ground is defined by a virtual EnergyPlus thermal zone. Freestanding objects (e.g. canopies and urban curtains) are taken into account for the shade they provide, but not for their longwave exchanges. Ground evaporation and transpiration are not considered. Autodesk CFD (35) provides Computational Fluid Dynamics and thermal simulation. It calculates MRT based on Finite Element Methods (FEM),. The thermal model is not validated for outdoor applications (36). The radiation model uses a flux-based method, but he latest version introduced a more accurate deterministic method. Each surface in the model is assumed to be a diffuse grey body model and directional dependencies are not considered (37). The human body is simplified and building operations are not taken into account. Free-standing objects' temperature is calculated according to conductive, convective and radiative flows. Ground evaporation and vegetation transpiration are neglected.

5. Discussion

The paper aims at establishing a preliminary list of the modelling variables that can affect MRT results. There are certain modelling assumptions and simplifications that emerge. The paper casts a bridge to future work that looks carefully at the implications of the operated assumptions. Table 4 shows the applicability of tools according to types of context. *CitySim Pro* suits the modelling of complex outdoor contexts. It has a complete definition of the shortwave and longwave radiation environment and allows to fully define building, ground and vegetation entities. *ENVI-met* covers a wide range of applications. It takes into account building, ground, vegetation, freestanding objects and water entities in its simulation. *RayMan* is a tool that suits preliminary MRT calculations of very simple context applications. RayMan results are dependent on the Sky View Factor input. Shortwave reflected radiation and longwave radiation exchanges are simplified and taken into account only for the ground. *Honeybee and Ladybug* could manage complex space modelling. Geometry outputs largely depend on EnergyPlus surface temperatures including for ground temperatures, which are modelled as a thermal zone. This leads to approximated predictions. *Autodesk CFD* has a series of limitations; radiation wavelength, directional dependencies and surfaces properties are roughly considered.

Table 4. Context of applicability of the tools

	CitySim Pro	ENVI-met	RayMan	HoneyBee & Ladybug	Autodesk CFD
Context with various ground types	Yes	Yes	No	No	No
Fields with simple buildings	Yes	Yes	Yes	Yes	Yes
Fields with geometrically complex buildings	Yes	Partially	No	Yes	Yes
Fields with free-standing objects (canopies and curtains)	Partially	Partially	No	Partially	Yes
Calm places (airflow)	Yes	Yes	Yes	Yes	Yes
Windy places	No	Yes	No	No	Yes
Contexts with trees and green entities	Yes	Yes	Partially	No	No

6. Conclusion

Researchers and practitioners move toward the modelling of outdoor microclimate and comfort conditions. Potential users are confronted with a lack of information about the tools' assumptions when accounting MRT and dependent Comfort Indexes. Tools are tested in action when simulating various and climatically different points for a specific site. The variables that impact MRT predictions in each of the tools are listed. The paper, filling a gap in existing literature, has collected and organized the fragmented information regarding the tools' calculation assumptions. The applicability of Outdoor Comfort Simulation tools in light of their MRT calculation assumptions is described.

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References

[1] Lindberg F, Onomura S, Grimmond CSB. Influence of ground surface characteristics on the mean radiant temperature in urban areas. Int J Biometeorol; 2016.
[2] Anon. NASA. Available at: climate.nasa.gov; 2017.
[3] Santamouris M., Kolokotsa D. Urban climate mitigation techniques, Routledge; 2016
[4] ONU. World Urbanisation Prospects. New York, United; 2014, p.32.
[5] Robinson D. Computer modeling for sustainable urban design. Physical principles, methods & applications, Earthscan; 2011.
[6] Naboni E. Integration of Outdoor Thermal and Visual Comfort in Parametric Design. International PLEA Conference, Ahmedabad, India; 2014.
[7] Mayer H, Höppe P. Thermal comfort of a man in different urban environments. Theor Appl Climatol 1987; 38:43–49
[8] ASHRAE Fundamentals Handbook 2001 (SI Ed.) American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2001.
[9] Thorsson S, Rocklöv J, Konarska J, Lindberg F, Holmer B, Dousset B, Rayner D (2014) Mean radiant temperature—a predictor of heat-related mortality. Urban Climate, 2014; 10(Part 2): 332–345
[10] Ali-Toudert F, Mayer H. Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. Theor Appl Climatol, 2007; 87:223–237.
[11] Lindberg F, Holmer B, Thorsson S, Rayner D. Characteristics of the mean radiant temperature in high latitude cities—implications for sensitive climate planning applications. Int J Biometeorol 58, 2013. pp. 613–627.
[12] Reinhart C, Fitz A. Findings from a Survey on the current use of daylight simulations during building design. Energy and Buildings, 38; 2006, pp.824-835.
[13] Naboni E. Integration of Outdoor Thermal and Visual Comfort in Parametric Design. International PLEA conference, Ahmedabad, India; 2014.
[14] Remund J, Müller S, Kunz S. Meteonorm. Global meteorological database. Version 7; 2015.
[15] Robinson D, Haldi F, Kämpf J, Leroux P, Perez D, Rasheed A, and Wilke U. CitySim: Comprehensive micro-simulation of resource flows for Sustainable Urban planning. BS2009 Proceedings, Glasgow, Scotland, 2009; pp.1083-1090.
[16] Coccolo S, Kampf J, Scartezzini J. L. Design in the desert. A bioclimatic project with urban energy modeling. 2013.
[17] Coccolo S, Mauree D, Kampf J, Scartezzini J.L. Integration of outdoor human comfort in building energy simulation database using CityGML energy ADE. 2016.
[18] Coccolo S, J. Kämpf, J.-L. Scartezzini, Outdoor human comfort and climate change. A case study in the EPFL campus in Lausanne, In: ICUC9 - 9th Int. Conf. Urban Clim. Jointly with 12th Symp. Urban Environ., 2015.
[19] G. Upadhyay, D. Mauree, J. Kaempf, J.-L. Scartezzini, Evapotranspiration model to evaluate the cooling potential in urban areas. A case study in Switzerland, In: Proc. Build. Simul. 2015, 2015.
[20] Bruse M. ENVI-met 3.0: Updated Model Overview, 2004; pp.1–12.
[21] Elnabawi H, Hamza N, Dudek S. Use and evaluation of the ENVI-met model for two different urban forms in Cairo, Egypt: measurements and model simulation. 2013.
[22] Song B, Park K, Jung S. Validation of ENVI-met Model with In Situ Measurements Considering Spatial Characteristics of Land Use Types. 2014.
[23] Jeong D, Park K, Song B, Kim G, Choi C, Moon B. Validation of ENVI-met PMV values by in-situ measurements. ICUC9, 2015.
[24] Bruse M. Die Auswirkungen kleinskaliger Umweltgestaltung auf das Mikroklima Entwicklung des prognostischen numerischen Modells ENVI-met zur Simulation der Wind-, Temperatur- und Feuchteverteilung in städtischen Strukturen. 1999.
[25] Ali Toudert F. Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate. 2005.
[26] Matzarakis A, Rutz, F, Mayer H. Modelling radiation fluxes in simple and complex environments—application of the RayMan model; 2007.
[27] Matzarakis A. Validation of modeled mean radiant temperature within urban structures. In: AMS, Fourth Symposium on the Urban Environment; 2002. pp. 72–73.
[28] Roudsari M., Pak M. Ladybug: A parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design; 2013.
[29] Roudsari M. Ladybug Primer. https://mostapharoudsari.gitbooks.io/ladybug-primer/content/; 2017a. [Accessed April 1, 2017].
[30] Roudsari M. Honeybee Primer. https://mostapharoudsari.gitbooks.io/honeybee-primer/content/text/components/Outdoor_Comfort_Analysis_Recipe.html; 2017b. [Accessed April 1, 2017].
[31] Roudsari M, Mackey C. Honeybee_Microclimate Map Analysis. https://github.com/mostaphaRoudsari/honeybee/blob/master/src/Honeybee_Microclimate%20Map%20Analysis.py#L285-L311; 2017. [Accessed April 1, 2017].
[32] Arens E, Hoyt T, Zhou X, Huang L, Zhang H, Schiavon F. Modeling the comfort effect of short-wave solar radiation indoors; 2015.
[33] Blazejczyk K. MENEX_2005 − the updated version of man-environment heat exchange model. 2005.
[34] Roudsari M, Mackey C. Honeybee_Microclimate Map Analysis. https://github.com/mostaphaRoudsari/honeybee/blob/master/src/Honeybee_Microclimate%20Map%20Analysis.py#L337-L435; 2017. [Accessed April 1, 2017].
[35] Autodesk. What's New in Autodesk® CFD 2016. 2016.
[36] Autodesk. Autodesk CFD 2016, Physical Models. http://help.autodesk.com/view/SCDSE/2016/ENU/?guid=GUID-3FCD44C0-8AAC-4826-B199-9D1C299F7165. [Accessed 1 April 2017].
[37] Autodesk. MRT Equation. https://forums.autodesk.com/t5/cfd-forum/mrt-equation/m-p/6915691#M14341. [Accessed April 1, 2017].