PHOENICS Case Study –Environmental:
CFD implementation of evapotranspirational (ETV) cooling by vegetation, by Harry Claydon, CFD Engineer, CHAM.

CHAM has recently implemented a new system for analysing cooling and humidity effects from vegetation. This capability has been in demand for some time and will help Urban Planners, Architects and Civil Engineers determine the impact of urban vegetation on pedestrian comfort.

The PHOENICS "Foliage" object has provided a means of specifying resistance of trees and bushes to prevailing wind. It now has the additional optional capability of specifying, within the defining attributes of the object, the EVT mass transfer rate of moisture from the leaves to the air, and the accompanying (negative) heat source. This means that for given species of tree, water supply and world location, architects and planners can simulate different arrangements of greenery within a site and determine the resulting impacts on the urban environment.

This article presents an example case to demonstrate the capabilities of this new feature, utilising values for the heat and moisture sources taken from literature. The Urban Heat Island (UHI) is the heating effect of man-made structures, such as buildings and roads, hindering ventilation and trapping solar radiation. It is well known that the heating effect of the UHI can be ameliorated by greenery. The main mechanism for vegetation's role in cooling air temperatures has been identified as having two aspects: shading and evapotranspiration, see Zhang (2019) [1]. The present simulation only concerns the evapotranspiration effects. Solar shading is handled separately by PHOENICS.

Figures 1 and 2 show the layout of the model used in this simulation. The detached houses on the street are modelled as cubes with triangular roofs; the detailed window and terrace geometry is not modelled in the simulation, for simplicity. The tree canopies on either side of the street are shown in Figure 1 as stylised trees, representing the real-life scenario; these are modelled for simplicity as continuous rectangular blocks of foliage. Each house is approximately an 18 m cube and is a standard PHOENICS blockage object with friction and with no heat transfer. The model setup is based on the model in fig. 2 of Xue and Li (2017) [2].

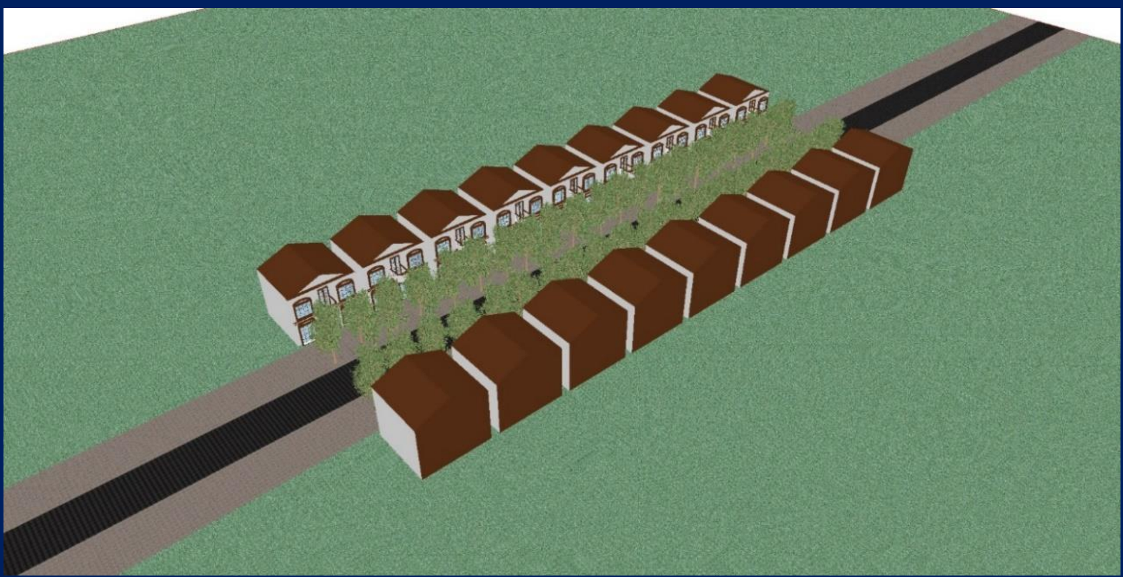

Figure 1: Street setup based on the model in Xue and Li (2017, fig.2) [2].
Two rows of detached houses are separated by a central road and two rows of trees.

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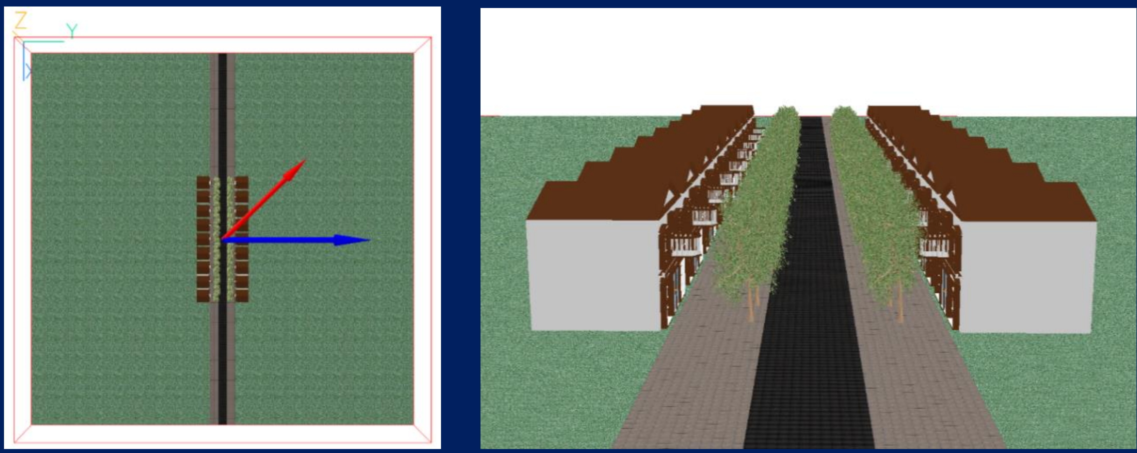

Figure 2: Plan view showing the prevailing wind direction at 45^{o} to the North (+Y) direction. Side view showing the view down the street.

The Leaf Area Density (LAD) used in this model was taken from the Leaf Area Index (LAI) divided by the average foliage height. LAI was set as "slightly dense", a value of 4, to represent a typical urban tree. LAD was therefore calculated as 0.33, based on a foliage height of 12 m.

The cooling power of the foliage object was set to 250 W·m^{-3} multiplied by LAD. This standard value of cooling power was taken from a paper by Zhang (2019) 1), and was validated using data by Gromke (2015) [3]. The moisture source was set to 810 g·m^{-2}·d^{-1} or 9.375e-6 kg·m^{-2}·s^{-1} again multiplied by the LAD; this was also taken from Zhang (2019) [1]. More values for specific species can be found in Mo et al (2007) [4].

It may be helpful to note that more plant-specific parameters are available in Breuer (2003) [5] for LAI and for stomatal conductance, which is used to calculate the moisture source. More complex equations are available in Gkatsopolous (2017) [6] for specific tree species to calculate more appropriate values for height/spread ratios, along with data for crop coefficients and stomatal conductance. Stomatal conductance is the measure of the rate of passage of carbon dioxide entering, or water vapor exiting through the stomata of a leaf.

The model prevailing wind was set to have a relative humidity of 50 %, ambient temperature of 20 °C, speed of 4.7 m·s^{-1} at an 18 m reference height at a direction of 45 ° to the +Y direction.

Figures 3, 4, 5, 6 and 7 show the results of the simulation. There is a decrease of up to 3 °C along the street at pedestrian level and an increase of up to 10% relative humidity. The majority of the street experiences at least 1 °C of cooling (Fig. 5 & 7) and 3% increase in humidity (Fig. 4) due to EVT effects. The apparent temperature is approximately 18 °C along the street due to the wind speed still remaining quite high (Fig. 3 & 6), however, on the leeward side of the buildings the apparent temperature increases due to stagnating air and lower wind speeds (Fig. 6).

Apparent Temperature is a general term for the perceived outdoor temperature, caused by the combined effects of air temperature, relative humidity, radiation and wind speed. The formulae for the Apparent Temperature used in PHOENICS-Flair are those used by the Australian Bureau of Meteorology. They are an approximation of the value provided by a mathematical model of heat balance in the human body. Two forms are given by the Australian Bureau, one including radiation (suitable for the working condition of people in direct sunlight) and one without (suitable for the working condition of people walking in the shade). The Apparent Temperature (TAPP) used here is the non-radiation version.

These results are in line with previous studies regarding vegetation's cooling effect; Zhang (2019) [1] and Gerogi et al (2010) [7] showed that the amount of maximum temperature reduction was similar at ~3 °C reduction through plant evapotranspiration.

Gromke (2015) [3] found that avenue-trees (as simulated here) were the most effective measure for reducing air temperatures. Cooling by facade greening was noticeable but less strong than by avenue-trees and roof greening did not result in noticeable air temperature reductions in the canyon. It was also found that cooling effects were restricted to the vicinity (≤ 10 m) of the vegetative measures; this is confirmed by the results of the present simulation.

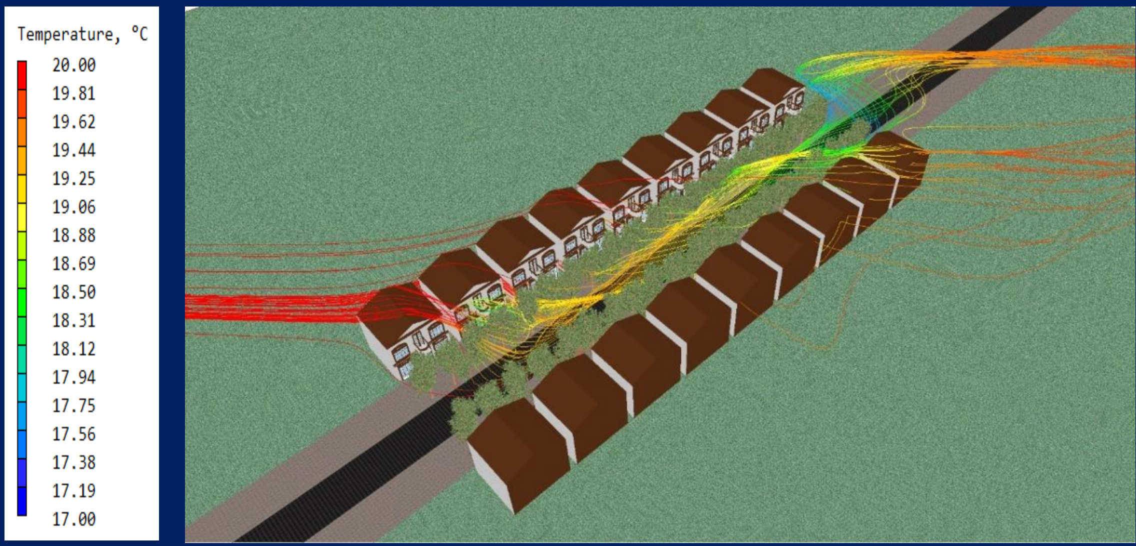

Figure 3: Streamline plot, coloured by temperature, showing the origin and destination of flow along the centre of the street at pedestrian level. Scale: Red – 20 °C; Blue – 17 °C

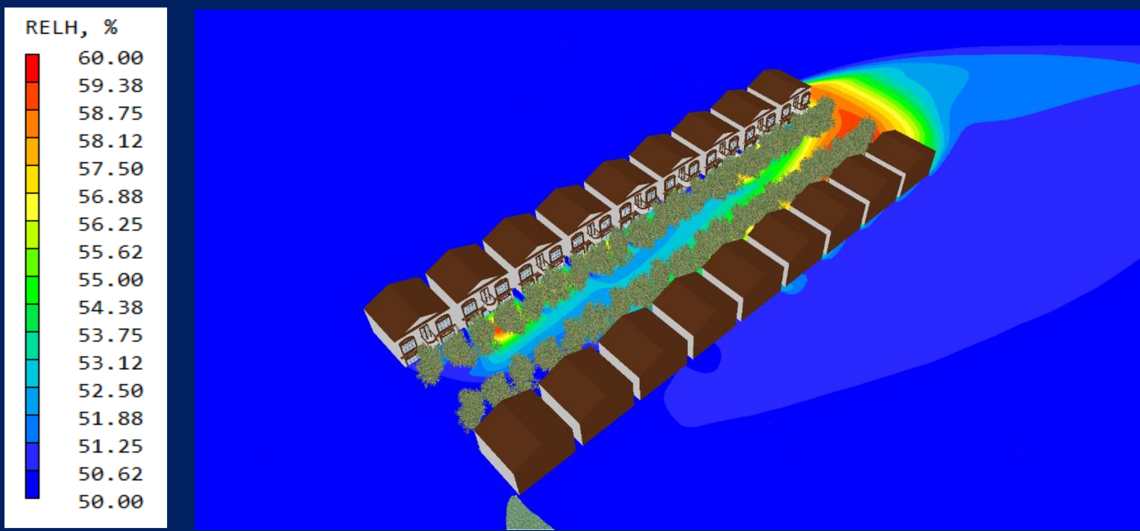

Figure 4: Contour plot of relative humidity at pedestrian level showing up to an increase of 10% humidity towards the leeward end of the street. Scale: Red – 60 %; Blue – 50 %

Konarska (2015) [8] states that transpiration of trees is "controlled mainly by the evaporative demand of air, soil water supply and the stomatal control of water loss". In the present simulation we have assumed that there is no lack of water which might hinder transpiration. This paper also states that "transpiration in darkness is often assumed to be negligible due to stomatal closure. However, several studies have reported non-negligible night-time stomatal conductance and transpiration of trees in natural stands". The present simulation is run assuming the maximum stomatal conductance and transpiration rate at midday (as imposed by the figures taken from Zhang (2019)), but this is variable depending on the weather conditions and time of day.

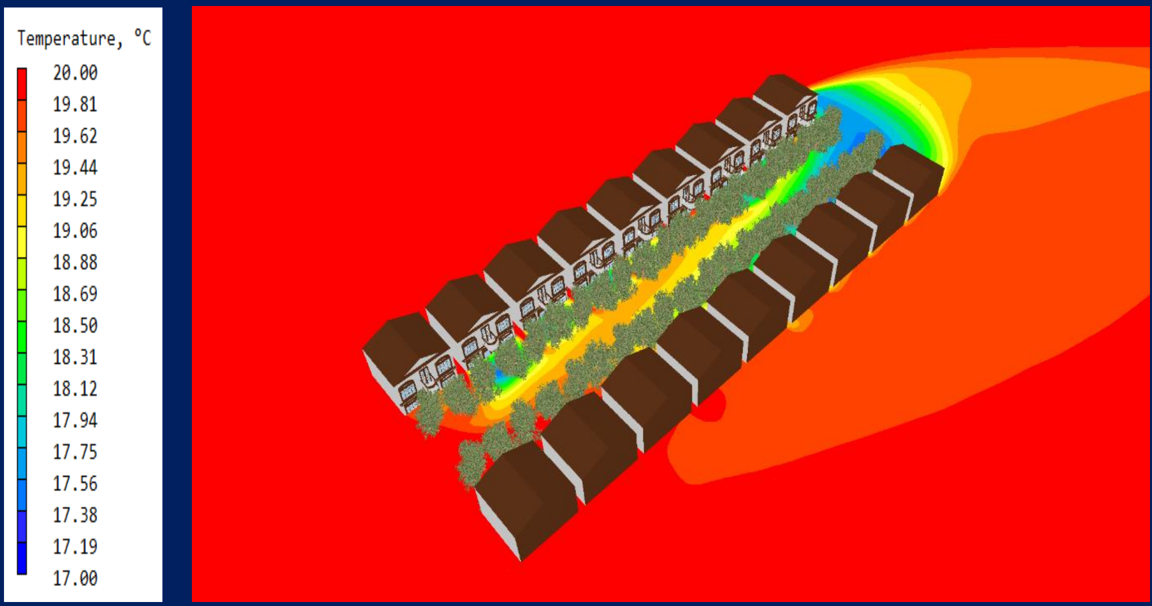

Figure 5: Contour plot of temperature at pedestrian level showing up to 3 °C of cooling towards the leeward end of the street. Scale: Red – 20 °C; Blue – 17 °C

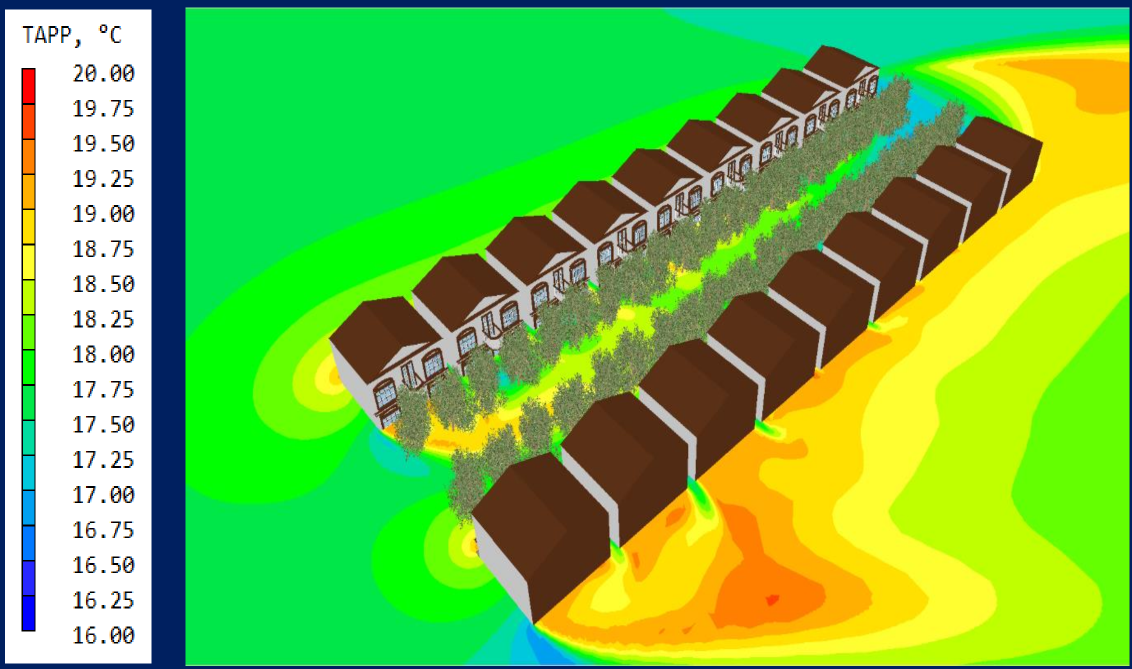

Figure 6: Contour plot of apparent temperature at pedestrian level showing up to 3 °C of cooling towards the leeward end of the street. Scale: Red – 20 °C; Blue – 16 °C

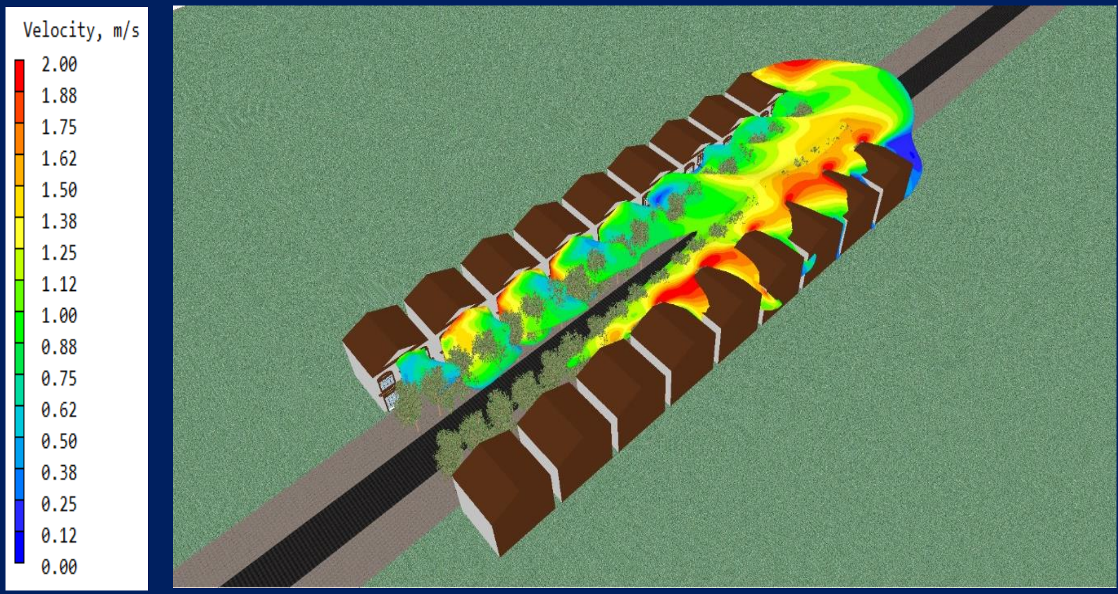

Figure 7: Iso-surface plot of temperature at 19 °C, coloured by velocity, demonstrating that the majority of the street experiences at least 1 °C of cooling due to evapotranspiration.

The paper by Zhang (2019) [1] examines how arrangement of vegetation affects microclimate air temperatures in an apartment housing complex, for various wind flows. It was found that a given total area of vegetation was more effective at reducing the air temperature when it was divided into smaller units, rather than being concentrated it in one place; and placing small vegetation spaces close to buildings was better than locating them centred between buildings which are further apart.

To conclude, this model has helped to illustrate how the new EVT feature embodied in the foliage object of PHOENICS can be used to simulate realistic effects of vegetative cooling. This article has also provided a brief review of some of the literature around the subject. This should provide a good starting point to help architects and urban planners who wish to model EVT in PHOENICS simulations.

References

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