2019

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Lloyd-Hill, D.

Lloyd-Hill, D. (2019) 'Designing an automated tool for natural ventilation', The Plymouth Student Scientist, 12(1), p. 247-262.

http://hdl.handle.net/10026.1/14688

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2019, **12**, (1), 247-262*

Designing an automated tool for natural ventilation

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Abstract

This paper aims to increase the number of natural ventilation systems utilised by building service engineers, which in turn will help to lower the environmental impact of their work. To do this an automated spreadsheet will be produced to help simplify the workload involved. This spreadsheet will initially utilise Etheridge's steady state envelope flow, a previously validated and widely accepted model for calculating air flow through a room. Currently a workbook has been produced in Excel that uses this model to calculate flow through a room that contains either a point heater or a vertically distributed heater. As well as this, the model can calculate the upper bands of temperature in the room while a steady state has been found between the heat loss and gain. It was concluded that in its current state the spreadsheet created does not allow the aim of the project to be reached. However, it does offer a good first step in the creation of a more robust spreadsheet that will allow the project aim to be met. It is also important to note that a list of recommendations for future iterations of the spreadsheet is given at the end of the paper, which if followed will allow this more robust spreadsheet to be created.

Introduction

Ventilation is and always has been a key part in the design of buildings, with the first purpose built buildings appearing as early as the Neolithic period (Etheridge, 2012). However, today's buildings are much more demanding when it comes to ventilation, with requirements for health and safety, energy consumption, as well as potential requirements for how the floor space is utilised and the productivity of occupants (Etheridge, 2012). With so many requirements to deal with, the fact that mechanical ventilation offers closer control of flow rates and internal air motion, often make it the more widely used system. This control is due to mechanical systems using ducts and fans to circulate air rather than relying on windows and cracks. As such, this paper details the maths behind and the process involved in creating a parametric spreadsheet that helps simplify the work needed to design a natural ventilation system.

Aims & Objectives

The aim of this project is to increase the number of natural ventilation systems used in buildings. The reason this is important is that natural ventilation offers several important advantages over mechanical ventilation. Firstly, natural ventilation systems have a smaller impact on the environment (Linden, 2001); the largest contributing factor of this is that natural ventilation does not require the use of electrical fans. Natural ventilation also typically offers lower capital, operational and maintenance costs (Designingbuildings.co.uk, 2017; Etheridge, 2012), though this is only guaranteed if the heat losses are less than that in a mechanical system (Etheridge, 2012). Finally, there is evidence to suggest that the occupants of a building prefer to both have control over their environment and to not be isolated from the external environment. While mechanical systems generally offer more control only natural ventilation systems satisfies both of these conditions (Etheridge, 2012; CIBSE, 2001).

Although natural ventilation offers some important advantages over mechanical systems, they are implemented less due to the current benefits of mechanical systems. Firstly, mechanical systems offer more control over the amount and source of the air which could lead to better comfort and indoor air quality, though Etheridge notes that this may in fact be deemed a positive value for natural systems (Mechanical Ventilation Breathe Easy with Fresh Air in the Home, n.d.; Etheridge, 2012). It is worth noting that natural ventilation systems struggle to provide cooling in hot humid climates unless combined with some form of cooling system, which could have a negative effect on the environmental impact (Etheridge, 2012). Mechanical systems are also easier to design than natural ventilation systems, this is because the maths involved are much simpler and mistakes are easier to correct, leading to reduced designer liability (Allard et al., 1998; Etheridge, 2012). This final advantage of mechanical systems is the one this project is going to attempt to counter, via the use of a parametric design spreadsheet created specifically for natural ventilation system designs.

To ensure that this aim is met a set of objectives have been decided upon. These objectives act as key milestones that will ensure that the aim is achieved if they are completed. Before the objectives were chosen, a rough scope of the spreadsheet needed to be decided upon. In the end, this project, and as such the spreadsheet, will focus on single room problems. The major factor in this decision was the timeframe for completing the project.

1. Research the fundamental principles and working mechanisms of natural ventilation
2. Research different methodology for natural ventilation system prediction, focusing on single room models
3. Decide on methodology and programme to be used to create spreadsheet
4. Design and re-design spreadsheet in a continuous iterative process
5. Test spreadsheet against real world examples or scale models

Deliverables

The deliverable for this project consists of a parametric spreadsheet that uses a theoretical model of the air and heat flow into and out of a room. This will allow a designer to enter a selection of known inputs into the spreadsheet and get a selection of key outputs out that regard the ventilation of the room.

Literature review

Fundamental Principles

Natural ventilation is defined by Linden et al as “the exchange of fluid between the interior of some space and its exterior environment when the flow is produced by naturally occurring pressure differences” (Linden et al., 1990). For natural ventilation systems these flows are either produced by the temperature difference between the internal and external air, or the action of the wind. They are used by designers to ensure that the internal air of a building is clean and at a comfortable temperature and humidity (Linden et al., 1990).

Before looking at the basics of natural ventilation, it is important to understand the fundamental principles of plumes. A plume is the upwelling of air above a heat source, so named due to its conical shape and in natural ventilation is - along with wind effects - what causes the movement of air. This movement is caused by the eddies in the turbulent flow entraining air into the plume from the sides, which in turn force air out of the top of the plume (Linden et al., 1990).

The first physical principle is the law of conservation of volume. Which in this case means that the volume of the fluid entering any horizontal slice of the plume, both via entrainment and vertically must equal the amount of fluid leaving the relevant horizontal slice of the plume vertically (Linden et al., 1990). The second physical principle comes from the steady flow energy equation which “states that during steady flow the net rate of energy transfer to a control volume by heat and work transfers is equal to the difference between the rates of outgoing and incoming energy flows by mass flow” (Cengel et al., 2017). This means that energy must be conserved, however for this to work conduction must be neglected, which it can be since plumes have a turbulent flow (Morton, Taylor and Turner, 1956). It is worth noting that these principles must also be upheld for the room as a whole.

The third physical principle is that the vertical profile of pressure is set by the hydrostatics of air outside the plume (Morton, Taylor and Turner, 1956). If Newton’s second law is applied to the plume, which "defines a force to be equal to change in momentum (mass times velocity) per change in time" (Grc.nasa.gov, 2017), it can be shown that the air inside the plume and the air being entrained into it must accelerate upwards under net force due to pressure profile and weight. This physical principle is based off The Morton-Taylor-Turner entrainment assumption which although has no first principle backing it up, has been showed to work well based off empirical evidence and has been used in journals since (Linden et al., 1990).

Room with single heat source

Now that the fundamental principles of a plume have been examined, it can now be placed inside a room with no openings, this will start to show the physics behind heating a building. In this example when the plume arrives at the top of the container it spreads out and forms a layer of lighter fluid (Worster and Huppert, 1983). This lighter layer will then be entrained by the continuing plume which will arrive at the top forming an even lighter layer. This layer will displace the previous layer downward producing a stratified region which is separated from the original fluid by an interface known as the first front (Worster and Huppert, 1983).

If two openings were added to the room, a flow will be driven through the openings, which will be entering through the bottom opening and leaving via the top opening. This flow will be caused by the difference in hydrostatic pressure between the denser fluid outside the space and the fluid inside (Linden et al., 1990). If left for enough time this will eventually lead to a steady state in which both the downward flow of lighter fluid reaches zero and the upward flow of denser fluid also reaches zero at the interface where the two meet. Although at this point the interface is stationary there is still a horizontal movement towards the plume due to entrainment and that any fluid entering the plume from the interface is immediately refreshed from above and below (Linden et al. 1990). By combining the physical principles mentioned above a set of equations can be constructed to predict the performance of a 2 opening, single heat source room.

Working mechanisms of a room with multiple heat sources

Up till now it has been assumed that there is only one heat source in the room, whereas in a real-world situation this is unlikely to be true. To start with the effects of several sources on the same horizontal plane will be looked at, if these sources have an equal power and are far enough apart that their plumes do not interact, then according to Cooper et al this will result in the same interface height with the same density difference (Cooper and Linden, 1996). However, if they have different powers, which is more likely, then a number of different layers will form equal to n+1 where n is the number of plumes with different powers. Each layer will have a density equal to the density of the plume feeding into it at the layer below (Cooper and Linden, 1996). For this project horizontally distributed heaters with different powers were not considered initially due to the complexity it adds to creating the spreadsheet. This complexity is caused by the fact that each additional interface can add extra terms to the pressure equation (5) depending on the opening height.

It also seems pertinent here to discuss the effect of a source distributed evenly over a vertical surface, in this case at a steady state you will end up with a layered density profile, with density decreasing as height increases, each of these layers will have the same vertical height. This is because the interface is formed when the volume flux of the plume is equal to the volume flux through the box (Linden et al., 1990).

Removing the heat source

Up to now, the effect of removing the source after it has been active for a time has not been examined. This is important as in a real-world situation rooms are not being continually heated but instead have their heat sources switching on and off to maintain the chosen temperature. If this occurs this will leave a room that is partially or completely filled with air of relatively light density. This will lead to a flow through the room, where the higher density fluid displaces the lower forcing it out of the room, caused by the difference between the hydrostatic pressures inside and outside the room (Linden et al., 1990). Eventually this difference will equal zero, this will stop the flow through the room and lead to an interface known as the neutral level (Linden et al., 1990).

Working mechanisms of wind on natural ventilation

Up to this point effects of wind on the flow rate have been ignored, this is a useful assumption to make, especially during early research, as including these effects could cause a large jump in the complexity of the maths involved. This size of this leap will depend on if a steady or unsteady flow model is used. Truly, a steady process is one where all quantities are constant and in terms of natural ventilation both changes in temperature and wind conditions are to be expected. The temperature changes will be slow enough that the unsteady terms will have little effect and as such buoyancy driven flows can be taken as steady (Etheridge, 2012). However, for wind driven flows this is unlikely to be true and as such should be taken as unsteady. Though this is not the case, and typically the time averaged wind values are used. This is because these values have a much slower rate of change, which again causes the unsteadiness to have less effect allowing it to be treated as steady (Etheridge, 2012).

Models

Now that the mechanisms behind natural ventilation are understood the various models that predict its behaviour can be researched.

Firstly, models that focused on rooms with single openings were looked at. Yamanaka et al (2006) tested the validity of two wind driven ventilation models for a single opening. He proved that one of these models was only true in certain conditions. As such for a room with a single opening the effect on wind can be found by applying the mixing layer theory (Warren, 1978). However, a general formula for airflow from both stack, wind, and other driving pressure differences does exist and is the power law for orifices (Zhai, Mankibi and Zoubir, 2015). It is also worth noting here that, unlike other models, for a room with only one opening the flows mix rather than displace each other.

Next models that focused on rooms with multiple openings were looked at. These models can be further split into those that consider just buoyancy and those that consider all driving forces. There are four major models that focus only on buoyancy, the first is Linden's "emptying water-filling boxes" (Linden et al., 1990) which forms the basis of much of the analytical modelling of natural ventilation. Next is Andersen's "fully mixed model" (Andersen, 1995), and finally Li (2000) created two models called "emptying air-filling boxes" and also compared the four models, showing that the other two were just special cases of his model (Zhai, Mankibi and Zoubir, 2015).

Finally, the models that consider all driving forces. Li and Delsante (2001) for example produced equations for the flow in both fully assisting and fully opposed wind. This is given as a cubic equation as a function of heat loss, buoyancy and wind and unambiguous solutions can be found if the temperature difference between the inside and outside is known (Andersen, 2007). Though this is useful it assumes that the wind is steady in direction and speed, which in a real-world situation is unlikely, as such it would be more useful to use Etheridge's quasi-temporal inertia model, which takes this into account (Etheridge, 2000). This model has been proven to be very accurate against previously published experimental data (Zhai, Mankibi and Zoubir, 2015) and was validated later by Chiu and Etheridge (2004).

For this spreadsheet Etheridge's quasi-temporal inertia model (2000) was not used initially, although it is very accurate at predicting the air flow, it was overly complicated for the first iterations of the spreadsheet. Instead it was built off Etheridge's pseudo-steady state envelop model, this is the model he derived his quasi-temporal inertia model from and as such offers a simpler, yet still combination driven model. As well as that it allows for easier upgrading to the quasi-temporal inertia model if wished for, as both use similar principles and formulas.

Methodology

Selection of Programme

The first step in creating this spreadsheet was to decide upon some important design choices. Some of these choices have already been made, for example the spreadsheet will only calculate values for a single room and will work using the steady flow envelope model. However, the programme the spreadsheet will be produced in is still undecided. In the end, Excel was chosen as its tabulated style allows for numerical data to be displayed easily and it's in built mathematical operations, especially goal seek, allowed for the parametric design spreadsheet to be created easier than other programmes (Akshaykumar et al., 2015).

It is also important to understand the outputs that designers are interested in knowing to ensure that the spreadsheet is fit for purpose. According to Etheridge (2012) the goal of a designer is to achieve the required flow pattern, and flow rates for a specified set of weather conditions. "In its simplest form this involves sizing and positioning all openings" (2012). Due to the software and model used, it was decided that to do this a parametric spreadsheet, that ensures volume is conserved would be produced. This would allow designers to alter environmental and window parameters so openings that allowed the requirements to be met can be found.

Uniform interior density

Once the programme was selected the first model could be built. This model was a box with 4 openings and a uniform interior temperature and density. Next, the calculations can be built up with the goal of ensuring total flow rate in and out equates to zero. The flow rate through an opening is given by Etheridge (2012) to be

$$q = SC_d A \sqrt{2 \left|\Delta p\right| / \rho} \tag{1}$$

Where q is flow rate (m3/s), S is the sign for Δp, Cd is the openings coefficient of discharge, A is opening area, Δp is the pressure difference across an opening, and ρ is flow density. Each of these terms will have a constant value apart from Δp, as such an expression for it is needed. Etheridge (2012) states that the pressure at a point is equal to the sum of its hydrostatic and piezometric pressures. As such the pressure difference between the openings can be expressed as the difference in these sums, and is equal to

$$\Delta p = P_E - P_{hE} - (P_I - P_{hE}) \tag{2}$$

Where P is piezometric pressure and Ph is hydrostatic pressure, where subscript I refers to interior and e refers to exterior. When the flow is inward this equation simplifies to only include the internal pressures, while the opposite is true for an outward flow. These equations have not been included as both will lead to the same equation to find the value for Δp (Etheridge, 2012), which is

delta p0	Roe	Roi	g					
-2.641181351	1.24	1.22	9.81					
opening	delta p	z	pw	s	Cd	A	ro	q
1	-2.033581351	2	1	-1	0.61	0.25	1.24	-0.27618798
2	0.789218649	8	5	1	0.61	0.25	1.22	0.173461699
3	3.985418649	7	8	1	0.61	0.1	9.81	0.054985389
4	3.004418649	12	8	1	0.61	0.1	9.81	0.047740895
								2.454903E-09

Figure 1: Picture of the layout of the first iteration of the tool

$$\Delta p = P_{hE0} - P_{hI0} - \rho_E g z + \rho_I g z \tag{3}$$

Where subscript 0 refers to the height, g refers to gravity and z refers to the height of the opening. If wind is present the external wind pressure is added to the external pressure giving

$$\Delta p = P_{hE0} - P_{hI0} - \rho_E g z + \rho_I g z + p_w \tag{4}$$

Where pw refers to wind pressure. Finally, the first two terms are grouped giving rise to Δp_0, this value will initially have to be estimated as P_{hI0} is not a constant and will take whatever value satisfies the continuity equation (Etheridge, 2012). Through these equations, a spreadsheet was produced that can calculate the flow through 4 known openings if the density inside and outside is known, as well as the wind pressure, shown in figure 1. It performs this by calculating values for q for each window using an approximation of Δp_0, it will then add these q values together giving rise to the total flow into/out of the building. Then a goal seek function can be performed setting q total to 0, ensuring volume is conserved, by altering the estimate of Δp_0.

2 density layers

The next step in creating this spreadsheet was to alter the model so it takes into account the presence of a heater. As discussed in the literature review, this will lead to two or more density layers in the interior of the room. For simplicity it was assumed that there was only a single heater or several with the same power distributed horizontally. This leads to a new equation for Δp if the opening is higher than the interface height.

$$\Delta p = \Delta p_0 - \rho_E g z + \rho_L g h + \rho_U g(z-h) + p_w \quad (5)$$

Where h is the interface height and subscripts L and U refer to lower and upper respectively. It is worth noting that by setting the values of the upper and lower internal temperature to be equal then this model also works for a uniform interior density. This revision also changed how the wind pressure is calculated, prior to this it was simply an input, which would require the designers to calculate its time averaged values out of programme. As such a formula given by Etheridge (2012) was added to find it, it is as follows

$$p_w = 0.5\rho_E U^2 C_p + p_{ref} \quad (6)$$

Where U is the average wind velocity, Cp is the specific heat capacity at constant pressure and p_{ref} is an arbitrary fixed reference pressure that from this point on is taken to be zero. It is also important to note that an input for the direction of the opening in relation to the wind flow. This input is either downwind for a positive p_w or upwind for a negative value. Density was also changed to no longer be a direct input and instead is found from the temperature at a location and a reference density using the following formula derived from Charle's law,

$$\rho_1 = \frac{\rho_{ref} T_{ref}}{T_1} \quad (7)$$

Where subscript ref refers to a reference value and subscript 1 refers to the opening. Several other useful outputs were added, including the total flow in, total flow out, system heat lose/gain, and air change rate. The formulas for the last two are as follows (En.wikipedia.org, 2018; Falke, 2018; Engineeringspreadsheetbox.com, 2018; and Arca53.dsl.pipex.com, 2018),

$$heat\ flow = \frac{m * C_p * T_f}{1000}\ (if\ S > 0)\ or\ \frac{m * C_p * T_E}{1000}\ (if\ S < 0) \quad (8)$$

$$ACH = \frac{q_{in} * 3600}{v} \quad (9)$$

Where m is mass flow rate, qin is the flow rate into the building and subscript f refers to the flow. The number of openings that could be inputted was also increased greatly. Theoretically speaking, the model used and spreadsheet created could calculate these values for an infinite number of openings. However, realistically there

Inputs					
Delta P0	0.8617905411617	wind velocity	5	room height	10
Density ext	1.24	Temp ext	10	width	10
Density Low int	1.22	Temp int low	15	length	10
Density High int	1.20	Temp int high	20	volume	1000
Gravity	9.81	ref density (20C)	1.2		
Interface height	3	Cp air	1004		

Outputs	
q total	6.77878E-08
Nat vent heat loss/gain	-5.44879543
ACH	2.15673725
gin	0.59909368
]gout	-0.59909361

openings	down/up wind	height	wind pressure coefficient	Cd	Area
1	down	2	0.25	0.61	0.25
2	down	8	0.5	0.61	0.1
3	up	2	0.25	0.61	0.25
4	up	8	0.5	0.61	0.1
5					

Figure 2: Picture showing layout of the 3rd iteration of the tool

are limits to the amount of space for openings to be placed and each opening calculated increases the time the spreadsheet needs to run for a solution to be found. As such the number of potential openings is initially set to 150 with the option for designers to add more manually. As well as alterations to the formulas present, several edits were made to the programme to improve its user friendliness at this stage. First all calculations were moved to a second sheet, this should help to ensure that no changes are made accidentally to the model by the user. Next inputs, openings and outputs were grouped together and tabulated. Finally, all inputs and openings were coloured green with outputs and Δp_0 coloured yellow. Though, technically an input Δp_0 was coloured yellow as its value changes during use. This is shown in figure 2.

Stratified density

The current programme can calculate the flow pattern for a set of known openings with 1 or more horizontally distributed internal heaters of the same power. However, as discussed in the literature review, the distribution of the heaters can also be vertical, if this is the case density stratification and therefore temperature stratification will occur. As such new equations to calculate T_f and Δp will need to be obtained. CIBSE (CIBSE, 2005) gives this formula to find T_f,

$$T_f = T_0 * \left(1 - \left(1 - \frac{T_0}{T_H}\right)\left(\frac{z}{H}\right)^n\right)^{-1} \quad (10)$$

Where H denotes reference height and n is the index value. Then by applying the binomial approximation to this equation it becomes

$$T_f = T_0 * \left(1 + \left(1 - \frac{T_0}{T_H}\right)\left(\frac{z}{H}\right)^n\right) \quad (11)$$

This can then be altered to make density the subject by using the ideal gas law, and finally it can be multiplied by g and integrated with respect to z to produce a formula for p, which is as follows

$$p = \rho_L g H \left(\left(\frac{z}{H} \right) - \left(1 - \frac{T_0}{T_H} \right) \right) * \left(\frac{\left({}^{z}/_{H} \right)^{n+1}}{n+1} \right) \tag{12}$$

And is detailed further in Etheridge (2012) as well as Caulfield and Woods (1998). This can then be added to the values for ΔP_0, the external stack, and wind pressure to give us a new equation to find Δp, as seen below

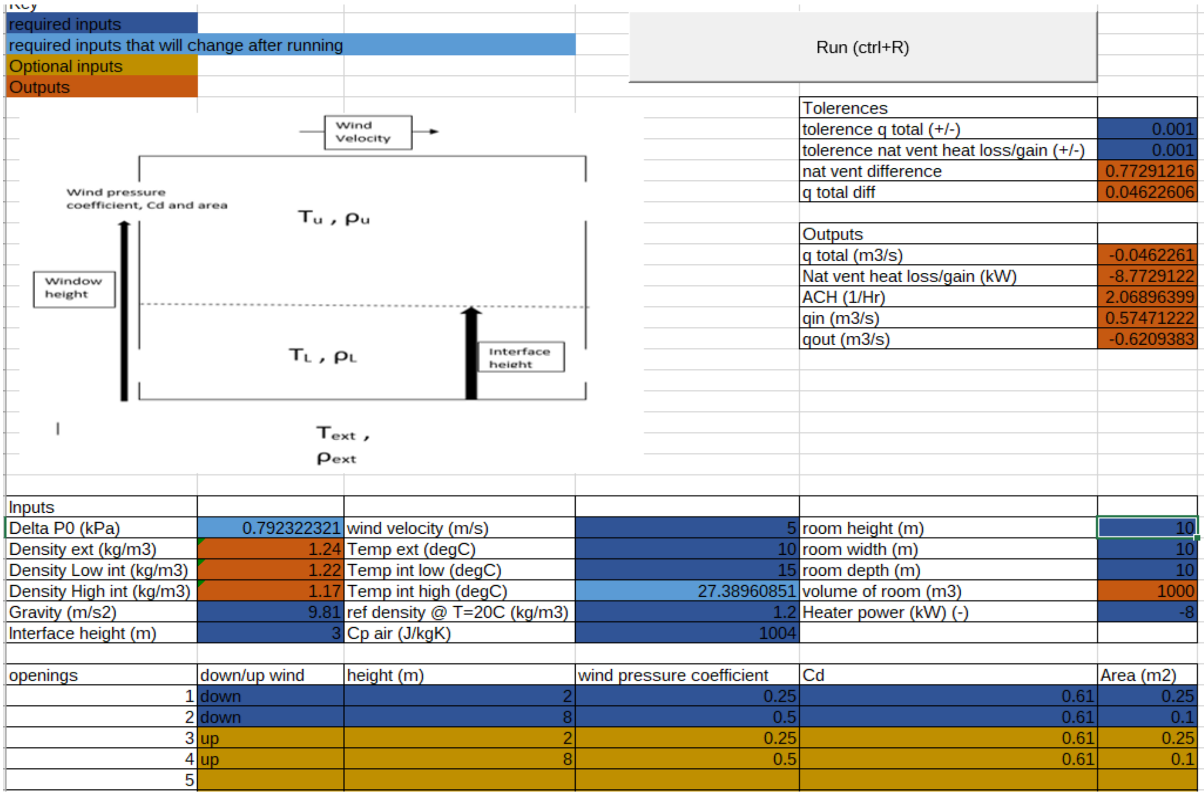

Figure 3: Picture showing 6th iteration of tool

$$\Delta p = \Delta p_0 - \rho_E g z + \rho_L g H \left(\left(\frac{z}{H} \right) - \left(1 - \frac{T_0}{T_H} \right) \right) * \left(\frac{\left({}^{z}/_{H} \right)^{n+1}}{n+1} \right) \tag{13}$$

Though some equations and inputs have changed the general workings of the spreadsheet remain the same as those described in the uniform interior density section. Now that parametric spreadsheets have been obtained for both vertical and horizontal/single distributions, focus was once again placed on improving the usability of the spreadsheet. The first step in this was combining the two spreadsheets into one. This involved renaming the individual sheets to ensure it was easy to see each sheet's purpose. Next the colour coding present was altered, firstly the number of groupings changed from 2 to 4. With inputs green, inputs that change blue, optional inputs yellow and finally outputs in red. A key was also added in the top of the spreadsheet to make this clear. These changes are shown in figure 3.

Steady State Temperature

Next it was decided that it would be useful to have the heat loss/gain of the system relate to a known heater power. This was done by using Excel's goal seek function to set the heat loss to the value of the heater power while varying the temperature of either the higher interface (point heater) or at the reference height (vertically distributed heater). This allows designers to see the temperature profile that would occur when a steady state is reached between the heater and the ventilation system. This also allows for the effects of removing a heat source to be predicted by setting the heater power to 0. However, trying to implement this change proved difficult, as Excel will not allow multiple goal seeks to take place simultaneously and as a result to get accurate results a long time-consuming string of goal seeks would have to be performed. Because of this, the following macro was written:

0. For i = 1 To 1000 (sets maximum number of iterations)
1. Range("f13").GoalSeek Goal:=0, ChangingCell:=Range("B26") (goal seeks q total to 0 by altering ΔP_0)
2. Range("f14").GoalSeek Goal:=Range("F30"), ChangingCell:=Range("D29") (goal seeks heat loss to the negative value of heater power by altering temperature)
3. If ("f10") < ("F7") And ("F9") < ("F8") Then GoTo 5 (if the difference between desired value and actual value is greater than the tolerance specified then go to step 5)
4. Next, I (run next iteration, if i=1000 will go to next step.
5. End Sub

This had two other major benefits, firstly for the macro to work correctly the values found must be checked against those desired to see if more iterations were required. Rather than simply checking the values against those desired, the difference between the two is calculated and then checked against inputs for the required tolerance of the calculations. This allows the designers more freedom when it comes to the precision of their calculations. As well as this the addition of the macro has also increased the simplicity of the spreadsheet as now rather than the designer using the goal seek function themselves all that is required is a press of the macro button which was added to the top of the spreadsheet.

With the addition of more inputs, the way the spreadsheet was laid out was re-visited, while much of the layout was not altered, a new table containing inputs and outputs related to the tolerance was added. Next the colours used for the key were looked at with more detail, and it was decided based on the work by Light and Bartlein (2004), that it should be changed as to better suit users with colour blindness. After this an extra sheet was added to the start of the workbook, this sheet contained instructions on how to use the spreadsheet, as well as a glossary of all terms found within the spreadsheet, as well as detailing how to add more openings. As well as this a diagram showing inputs in relation to the room and a graph detailing how the value of the index n affects the temperature profile. Finally, all non-input terms in the workbook were locked to prevent any changes that could damage the model, though a brief description on how to unlock it was added to the instructions sheet.

Uncertainties

There are 2 main types of uncertainty found in these calculations and they are those caused by assumptions made and those caused by the input data. This section will focus on the latter with the assumptions made being talked about in the next section.

- The first source of input uncertainty comes from uncertainty in the value of Cd used for openings. Though the values are independent of Reynolds number, there is still a large amount of uncertainty caused by installation effects (Etheridge, 2012).
- As well as this the presence of adventitious openings, which tend to be small unintentional openings such as cracks, can lead to leakage. This adds additional uncertainty, though it should be noted that nowadays, due to leakage standards only the overall leakage matters, which is easier to calculate accurately and as such this can lower the uncertainty (Etheridge, 2012).
- The value chosen for Cp and wind speed will also cause some uncertainty. This is because Cp is dependent on the wind direction, and while the designer will know the value for wind direction and wind speed at a meteorological station it is likely this is far removed from the building in question. This uncertainty can lead to quite a large change in q if the situation arises where buoyancy effects are negligible. However, when wind is negligible the uncertainty from this will be zero (Etheridge, 2012).

Assumptions

Several assumptions have been made in the model used above and they will now be summarized.

- It is assumed that the openings value for Cd is independent of the Reynolds number. This is a reasonable assumption to make as short purpose-built openings such as air vents and small windows do have independent Cd values thanks to their shape.
- The hydrostatic equation applies to the air inside the building, this is reasonable as the velocity of the air inside the building will typically be small enough that the pressure caused by it is neglectable. This may not be true if ventilation rate is high and Δp is low (Etheridge, 2012).
- The external wind pressure surrounding the opening is given by the pressure in the absence of the opening. For small openings this is reasonable, but not for very large openings.
- For determining density, it is assumed that the pressure changes are small enough so that it can be treated as incompressible. This means that the equation of state requires only temperature. Another assumption was made about the density, this is known as the Boussinesq approximation, and it states that density differences can be neglected in the Navier-Stokes equation, where they affect the acceleration term (Etheridge, 2012).

- The flow in the region of the inlet and outlet is the same as when Cd is found in a lab. Realistically this is not the case as the presence of wind can have significant effect. Etheridge (2012) suggests running tests on a model with uniform density to find appropriate Cd values.

Validation of spreadsheet

As stated in the objectives, validating the spreadsheet is an important aspect of reaching the aim of this project. Ideally, a scale model of a room would be built up and various dimensional numbers would be calculated via experimentation. These could then be comparted with the same dimensionless numbers found via use of the spreadsheet and graphs could be drawn up to compare values. Unfortunately, due to time constraints this was unable to be performed. However, instead of this a comparison between the dimensionless numbers calculated via the spreadsheet and that experimentally found from other authors will be used. The data that is being used to validate the spreadsheet comes from Hunt and Linden (2005) and it requires a new set of equations to be created for the validation. These equations are shown below and are given in Hunt and Linden (2005).

$$F = \left(\frac{\Delta p_w}{\rho}\right)^{\frac{1}{2}} * \left(\frac{A * Cd * \sqrt{2}}{BH_p}\right)^{\frac{1}{3}} where\ B = \frac{g * HeaterPower}{Cv * P_E * T_E} \qquad (14)$$

By plotting the value of F against h/H_p with a known value of A^*/H^2 we can check the values produced by the spreadsheet, the values obtained were compared with the results obtained by Hunt and Linden and the 9 results matched fairly well with the expected results, with all of them being in the same order of magnitude as those found experimentally. Because of this, and the fact that the model used has been experimentally validated prior to this by several sources including Carey and Etheridge (1999), Chiu and Etheridge (2004) and Etheridge (2012), it is reasonable to assume that the model present in the spreadsheet can predict important aspects of natural ventilation to a reasonable level.

Conclusions

This project aimed to increase the number of natural ventilation systems used in buildings by means of a spreadsheet used to calculate steady flow air rate in a room. However, it was found that in its current state, the process was not robust enough to pursue. The main reason the aim has not been met is due to the large scope of the project and the relatively short amount of time available. Due to this issue, objective 4 – the design and redesign of the spreadsheet - had less iterations than desired. However, the spreadsheet does offer a good first step towards the aim and it is the author’s hope that the recommendations given at the end of the paper will be used as guidance for future revisions that can be made to the spreadsheet so that the aim can be met in the future.

Recommendations

While the spreadsheet is currently in a workable state, there are several changes that could be made that would produce a more robust spreadsheet that may increase the use and interest of natural ventilation systems in buildings, and these will be summarized below:

- Openings with a non-zero height, such as chimneys cannot be modelled at the moment. If it is assumed that the density inside these openings is uniform then this may be done by simply adding a ρgL term to the formula for Δp.
- Currently only horizontal distributed heaters of the same power can be modelled, this could be improved if a selection was added for number of heaters (n), which in turn created a number of interfaces equal to n+1. Though this may cause additional problems as for this to be modelled correctly values for each interface temperature would have to be known.
- As mentioned during the Models section of this paper the model chose assumes that the flow is steady, as such it is recommended that the model be changed to Etheridge's (Etheridge, 2000) quasi-temporal model, this should be made easier as it is derived from the model used.
- It is also recommended that calculations be added that find the total leakage through adventitious openings, Etheridge (2012) offers calculations showing their effect.
- Finally, and perhaps the most important change recommended, is altering the spreadsheet so it operates on a multiple room model rather than a single one. The reason this is so important is that for this spreadsheet to become useful for designers, it must be able to model full buildings rather than single rooms.

Acknowledgments

I would like to offer my gratitude and thanks to several people who without this project would not be possible. First, I would like to express my gratitude to Daniel Hatton, my project supervisor, for his enthusiastic help in directing my studies and checking my work throughout this year. Next I would like to thank my mother as without her I would not have had the opportunities that have been provided me and allowed me to get to where I am today. Finally, I would like to thank my partner for her continued love and support that has helped me remain strong even during the most trying times.

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