Reconsidering the Wetness Fraction in Geothermal Heat Transfer Modelling

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ABSTRACT: The study reviews the current practice in underground mine heat modelling of distributing geothermal heat between its sensible and latent components. A commonly used technique is to define an equivalent wetness fraction to model both the latent heat transfer component as well as the elevated total heat transfer through the rock resulting from the presence of the moisture, while also averaging out the variations in water distribution around the perimeter of the tunnel. However, the wetness fraction has some shortcomings, most stemming from its accounting for several different physical properties of the rock structure and wetness distribution. This makes it difficult to conceptualise and calibrate, as well as to apply previous experience from one mine to another. A further limitation is that the method used for modelling geothermal latent heat transfer in steady-state heat simulations cannot be used for dynamic heat modelling, which has become of more relevance recently, with higher risk factors associated with high temperature mines and refrigeration and the greater analytical opportunities afforded by modern computing. This study first reviews the wetness fraction application in steady-state geothermal heat modelling. It then discusses the parameter's shortcomings and challenges in calibrating. Finally, it demonstrates the alternative procedure needed for dynamic geothermal heat modelling and validates it against the steady-state method. The alternative procedure effectively proposes a rescaling of the wetness fraction, the advantages of which are discussed. This rescaling can either be incorporated into the dynamic model alone or instead applied to wetness fractions for all modelling methods. Regardless, the method establishes the good agreement between the dynamic modelling and the steady-state modelling of geothermal latent heat transfer in fully and partially wet airways.

1 INTRODUCTION

As underground mines grow deeper and further into hotter ground, managing geothermal heat becomes critical, and heat modelling can be used to identify problem areas in terms of high wet bulb temperatures or to assess the need for primary or spot refrigeration. Additionally, in very hot mines, risk analysis around failure or scheduled downtime of refrigeration units may require transient modelling of heat effects. To this end, recent work has focussed on dynamic heat modelling (Griffith, 2024, Griffith & Stewart, 2019, Carstens, Ilg & Pospisil, 2022, Yi, Ren, Ma, Wei, Yu, Deng & Shu , 2019, Hefni, Xu, Zueter, Hassani, Eltaher, Ahmed, Saleem, Ahmed, Hassan, Ahmed, Moustafa, Ghandourah and Sasmito, 2022) where the variations in time of the temperatures in the mine are modelled. The main challenge in this regard is the modelling of the heat capacitance of the underground rock mass, which typically cools over a 5 year time span, and then more slowly after that. This can be well modelled in a steady-state manner using the Gibson function (McPherson, 1993), assuming constant forcing air temperatures over the life span of the model. However, changes in heating or cooling (such as during a shutdown) cannot be easily included, nor can seasonal variations of temperature.

In the author's recent work (Griffith, 2024), a method for modelling the variation of geothermal rock heat over time for a small network of airways was presented and validated against previous work by Danko, Bahrami, Asante, Rostami and Grymko, 2012. Demonstrated there was the possibility of modelling a large change in heating or cooling conditions in a mine. For example, if a refrigeration unit is running for a substantial period, then the rock wall along the path of the chilled air will be cooled. If the refrigeration unit is switched off, then the capacitance of the rock wall will absorb heat from the unchilled air and the downstream temperatures will rise more slowly as a result. Also investigated were the differences between the steady-state heat simulation method and dynamic heat simulation with seasonal variation.

In that work, to simplify the development and the analysis, an assumption of dry airways was made, meaning that there was no latent geothermal heat transfer. The question of including latent heat transfer in the dynamic heat solver (as it is included in existing Gibson-based steady-state geothermal heat calculations) has been left to this paper.

This paper will give background on and review how geothermal latent heat transfer is handled in the existing Gibson function-based steady-state geothermal heat model. This will include a discussion on the use of wetness fraction and what it represents, along with some of the limitations of the parameter. The paper will then describe how this can be handled in the dynamic heat context and propose a change to the way that wetness fraction is applied generally.

2 BACKGROUND

The method for steady-state geothermal heat transfer presented in this background section is taken almost entirely from McPherson, 1993. Assuming negligible longitudinal variation in heat transfer and assuming a cylindrical tunnel, the heat transfer occurring at the rock-to-air interface from the rock mass to the air in the tunnel can be simplified to the radial dimension only and represented by:

$$q = k\left(\frac{\partial\theta}{\partial r}\right)_s = h(\theta_s - \theta_d) \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

where:

K is the thermal conductivity of the rock [W/(m°C)]

θ is the temperature [°C], *r* is the radial coordinate [m]

h is the heat transfer coefficient for heat transfer from the rock surface to the air, a function of the airway roughness and the flow speed [W/ (m^2°C)]

θ_s is the temperature of the rock at its surface, or at its interface with the air and

θ_d is the dry bulb temperature of the air (the forcing temperature), with the subscript $_s$ representing a value at the rock surface (or the rock-to-air interface).

However, the rock cools over time, beginning at its virgin rock temperature (VRT), so a model for the cooling of the rock deep into the wall is required. Again simplifying to one-dimensional radial conduction, but also assuming an infinite rock mass around the tunnel, the cooling of the rock can be modelled using the equation:

$$\alpha\left(\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}\right)=\frac{\partial\theta}{\partial t} \qquad \left[\frac{°\mathrm{C}}{\mathrm{s}}\right]$$

where,

α is the rock thermal diffusivity [m^2/s]

and t is time [s] (Danko et al 2012, McPherson 1993).

It is computationally costly to solve this equation for each of the thousands of airways in a typical mine model, so a simplified method, based on the Gibson function (McPherson 1993), was developed in the 1970's, that returns the heat flux for a given airway as a function of its age, rock thermal properties, air velocity and temperature. It allows the accurate calculation of heat flux from a handful of steps and is far less intensive than solving for all the heat variation into the rock. This is particularly useful for a network heat simulation which needs to have the heat transfer from thousands or tens of thousands of airways. The function has several necessary simplifications, such as the assumption of a constant air temperature over the life of the airway, the implications of which are discussed in Griffith, 2024 and Griffith & Stewart, 2019.

McPherson, 1993 is the most useful and accessible reference for the method and is not described in full. In summary, the method resolves to the equation for the heat transfer at the surface-to-air interface per unit area of exposed rock:

$$q=h\frac{G}{B}(VRT-\theta_d) \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

Where G is a dimensionless temperature gradient at the rock surface (obtained from the Gibson Function) and B is the Biot number, a dimensionless heat transfer coefficient.

With the thermal properties of the rock, all the information is available to calculate the geothermal heat transfer for an airway. However, we know that latent heat will be an important component of this heat exchange. We know this from the heat transfer equation, which relies on the temperature difference between the rock wall surface and the dry bulb temperature; dry bulb temperature will vary significantly with variations in evaporated moisture in the air. This is observable in underground mines, where the latent heat component of heat transfer (from geothermal heat, surface air intake, diesel engine exhaust and from vehicular heat) is known to have an important effect on temperatures underground and also on the formation of underground fog (Stewart & Loudon, 2024). Further, it is known that a wetted surface – while affecting the sensible to latent heat ratio – will also generally increase the total heat transfer from that surface, due to the extra heat transfer from evaporation. (For the descriptions below, it will be assumed that evaporation is occurring, but condensation of water on the rock wall is also modelled by the same method.)

Figure 1 shows a typical scenario for a geothermal heat transfer in an underground mine. The dry surface has a temperature difference with the dry bulb temperature of the air, leading to a flow of heat energy from the rock into the air, with the rock cooling over time. With a wet surface, the evaporation of the water leads to an increased flow of sensible heat from the rock and, in this case, a negative flow of sensible heat from the rock to the air, to accommodate the evaporation rate. In this scenario the sensible heat flow from the rock to the air may be positive or negative, depending on the latent heat transfer required to satisfy the evaporation and the total heat transfer from the rock.

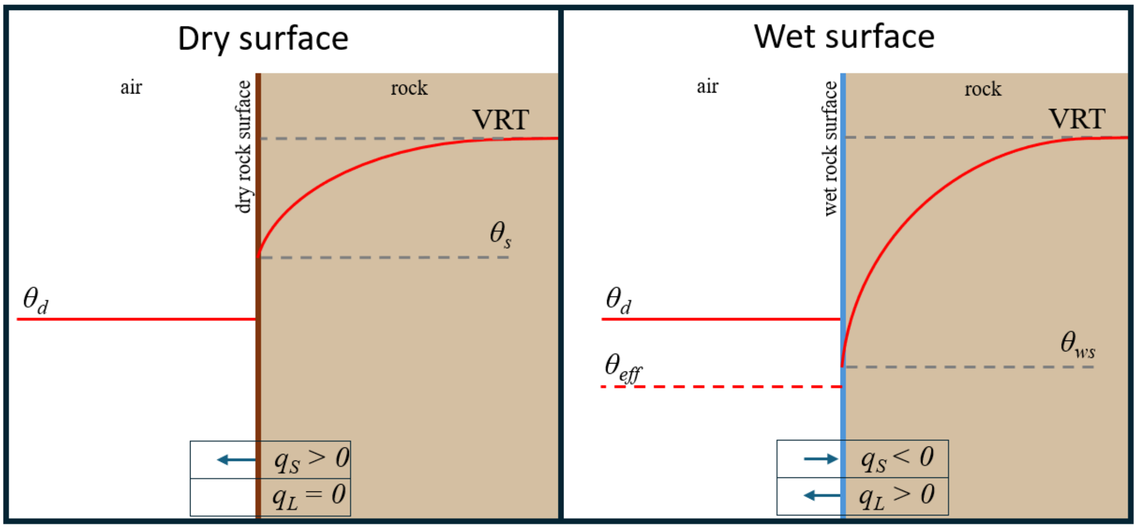

Figure 1 At left, heat transfer through the dry surface, at right, the same but with a wetted surface. In this case, the wetted surface leads to a latent heat transfer which draws heat from both the air ($q_S < 0$) and the rock, but leading to a greater overall heat transfer ($q_S + q_L$). Also shown is the effective dry bulb temperature, θ_{eff}, giving the same overall heat transfer for an equivalent dry surface.

An approach to model this is outlined in McPherson, 1993. Firstly, the sensible and latent heat components are equal to

$$q_L = \frac{0.0007 h_c L_{ws} (e_{ws} - e)}{P} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

$$q_S = h_c (\theta_{ws} - \theta_d) \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

Where h_c is the convective heat transfer coefficient (a function of the air speed and tunnel roughness), L_{ws} is the latent heat of evaporation at the wet surface temperature, e_{ws} is the saturated vapour pressure at the wet surface temperature and e is the actual vapour pressure. With this, it would be possible to calculate the heat flows, except the wet surface temperature is unknown.

The method in McPherson, 1993 gets around this by supposing an equivalent dry wall case, using an effective dry bulb temperature θ_{eff}, rather than the true dry bulb temperature. This effective dry bulb temperature is lower than the true dry bulb temperature, representing the increased total heat transfer occurring because of the wet surface. This is also shown in figure 1 in the right panel. The total heat transfer, using the standard equation from before can be written as

$$q = h \frac{G}{B} (VRT - \theta_{eff}) \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

To assist in determining the wet surface temperature, and therefore determining the sensible and latent heat transfer flow, the method finds another equation for the strata heat, independent of the above equations for sensible and latent heat at the wet surface. The first step is to take the original equation for the temperature at the rock surface (equation 15.20 in McPherson, 1993):

$$\theta_s = \frac{G}{B} (VRT - \theta_d) + \theta_d \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

and then using the form of this equation, create the following relation for the wet surface:

$$\theta_{ws} = \frac{G}{B}\left(VRT - \theta_{eff}\right) + \theta_{eff} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

by replacing the dry surface temperature with the wet surface temperature and the dry bulb temperature with the effective dry bulb temperature. Rearranging and substituting gives the following relation for total strata heat as a function of wet surface temperature, independent of the equations for sensible and latent heat.

$$q = h\frac{G}{(B - G)}(VRT - \theta_{ws}) \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

With this set of equations for q, q_S and q_L, (as well as the equation $q = q_S + q_L$) the wet surface temperature can be determined by using an iterative root-finding method to satisfy the equations and then the sensible and latent heat flows calculated.

3 PROBLEMS

A problem with this method in its application to underground mines is the water flow rate from the rock to the air. Latent heat in air is essentially a representation of the amount of evaporated water in the air. If we account for the heat energy in the air using enthalpy referenced to 0°C (or using the sigma heat concept (McPherson 1993)), then the latent heat component in the air is the amount of energy required to evaporate the water contained in the air at the current wet bulb temperature of the air. Therefore, as well as being represented as an amount of energy, the latent heat can be represented as a mass or a volume of liquid water. For a given wet bulb temperature, the latent heat of evaporation and relation between latent heat flow (W/m^2) and water mass flow per unit area of exposed rock surface is

$$L = 2502.5 - 2.386\,\theta_w \qquad \left[\frac{\mathrm{kJ}}{\mathrm{kg_{H_2O}}}\right]$$

$$\dot{m}_{\mathrm{H_2O}} = \frac{q_L}{1000\,L} \qquad \left[\frac{\mathrm{kg_{H_2O}}}{m^2 s}\right]$$

With the method described earlier for heat transfer at wet surfaces, the water flow rate from rock to air is being set by this method according only to the difference in vapour pressure between the rock surface and the air. So an assumption exists that there is a water flow rate sufficient to replace the evaporated water. If conditions change (for example, the wet bulb temperature is reduced) and more water is evaporated, the method above assumes that the water flow rate is increased. But the available water may be insufficient; if so, then the rock will dry out and a lower proportion of the rock wall will be wet.

The wetting of surfaces in an underground mine is highly variable. The entire floor of the tunnel may be wet; or the moisture may be confined to a narrow channel to the side; there may be dampness up part of the wall; or concentrated flows of water from the wall at intermittent distances down the tunnel; there may be moisture distributed evenly over the wall or concentrated in troughs in the wall roughness. The water may also be evaporating in a different manner – the physics over how a free surface of water gives off latent heat are different to those of a wet solid. To account for this an equivalent wetness fraction is applied; it is a value of between 0 and 1, defining the fraction of uniformly wet surface that would give the same rates of heat and moisture transfer as the actual surface with non-uniform wetness. According to the method in McPherson, 1993, the wetness fraction then sets the ratio between how much of the rock strata heat is determined via the method described above for wet surfaces, and how much is determined via the dry wall method. For the remainder of this paper, this method will be referred to as the split method. The split method interestingly breaks the azimuthal symmetry of the radial heat transfer model, effectively modelling two potentially very different rock temperature distributions in the same cross-section; in the example presented in McPherson, 1993, the dry section of the wall has a surface temperature of 26°C, while the wet surface temperature is 18°C. There is no accounting for this in the one-dimensional radial heat conduction and convection equations upon with the method is based. The issue is mentioned briefly in McPherson, 1993, but not explored in any depth (section 16.3.1.1) and the author is not aware of this being discussed or explained in some other literature not referenced here, but it may well have been. Nonetheless, with wetness fractions defined and used as such, from observation, in the driest of mines wetness fractions are no less than 0.04; 0.15 is a standard default value, while a wetness fraction of 0.8 represents a very wet mine.

In a model with a wetness fraction calibrated with observed date, the wetness fraction will be doing several things at once. It will be accounting for the distribution of water flows over the wall and the floor (evenly distributed wetness or concentrated flows, which would likely depend on the condition and permeability of the rock), for the maximum allowable flow rate of water from the geothermal water source and indeed for the capacity of unevaporated water to either leave or not leave the rock at all or to enter exposed or unexposed waterways in the mine. Furthermore, due to the symmetry-breaking division of dry and wet treatments, the wetness fraction may also be correcting for unknown azimuthal variations in heat conduction in the rock and convection in the air.

It is unsatisfactory that a key parameter in the geothermal heat transfer is one that does not have a well-defined physical basis. This means one cannot take the wetness fraction from one mine and confidently apply it to another, nor be confident of the wetness fraction during the design phase of a mine.

4 DETERMINING WETNESS FRACTION

The main method of calibrating the wetness fraction in an existing mine is by comparing the dry bulb and wet bulb temperatures between the model and the mine. While the wetness fraction will influence the total geothermal heat, it is primarily influencing the ratio of sensible to latent heat. The wet bulb temperature is a near-direct measure of the amount of heat energy in the air, so it will change mostly in response to a change in total energy input and less so to a change in the sensible to latent heat ratio. Therefore, a significant difference in simulated and observed wet bulb temperatures is generally an indication that an important heat energy source has been left out or incorrectly configured. Similar simulated and observed wet bulb temperatures indicates the total heat input is well modelled, at which point the dry bulb temperature can be compared.

The dry bulb temperature will depend strongly on the sensible to latent heat ratio, therefore it will depend strongly on the wetness fraction in a mine where geothermal heat is a significant heat source. A well-matched wet bulb temperature with an overestimated dry bulb temperature would generally indicate air that is too dry and a wetness fraction that is likely too low. Increasing the wetness fraction will increase the moisture in the air (as well as the total heat) and bring down the dry bulb temperature.

Another way to calibrate is to examine the moisture flows in the mine. A network heat simulation software will provide evaporated moisture flows at the mine inlets and outlets, as well as at other moisture sources (such as diesel engines), meaning that the geothermal heat contribution to the moisture flow for the total mine can be obtained either directly, or derived from other sources. A similar exercise can be done at the mine; for a given moment, or day, determination of the moisture flows at the inlets and outlets can be done by means of a temperature and flow survey, meaning an estimation can be made of how much water is being evaporated in the mine. These can be compared and calibrated between the mine and the model.

5 DYNAMIC HEAT

For the dynamic heat solver which simulates the variation of heat in the rock over time, a method of applying the wetness fraction needs to be created. For the steady-state solver, the Gibson function can be used to establish a new equation for the effective dry bulb temperature; but this equation is based on the VRT and relies on a constant forcing temperature over the life of the tunnel. For the dynamic case, the VRT is not a useful parameter, since the solver needs to include the history of the tunnel stored in the rock wall temperature distribution, which could take any form.

Fortunately, in this case we are not as restricted as in the steady state case, nor do we require an effective dry bulb temperature. In the dynamic solver, the heat in the wall is simulated from its inception, so at all times the wet surface temperature is available and the latent heat flow, q_L, can be calculated from the existing equation.

$$q_L = \frac{0.0007 h_c L_{ws} (e_{ws} - e)}{P} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

For a situation of evaporative geothermal heat transfer, this additional heat transfer from the evaporation will increase the heat flow from the rock as needed, reducing the rock surface temperature and coupling with the sensible heat transfer, driven by the dry bulb and wet surface temperature difference.

This can be tested by comparing with an example from McPherson, 1993, section 15.2.9. In the example, we have: an airway of width 3.5m, height 2.5m and length 20m; Atkinson friction factor 0.014 kg/m^3; airway age 3 months or 7,884,000 seconds; airflow 30 m^3/s; dry bulb temperature 25°C; wet bulb temperature 17.9°C; barometric pressure 100 kPa; rock thermal conductivity 4.5 w/m°C; rock density 2200 kg/m^3; specific heat 950 J/kg°C; and virgin rock temperature VRT 42°C.

The steady-state Gibson-based method returns a total strata heat flow per unit area of exposed surface of 36.1 W/m2. This example is for an entirely wet surface (wetness fraction = 1), so the latent heat flow from the rock is 184.2 W/m^2 (or 0.075 mg$_{H20}$/m^2) and the sensible heat flow is -148.1 W/m^2, indicating a latent heat flow drawing sensible heat from both the air and the rock. In the example, the wet surface temperature is 18.17°C , less than the 25°C air dry bulb temperature.

For the dynamic heat solver - in addition to the rock wall temperature distribution and the variation over time – a result is returned of latent heat flow 191.06 W/m^2, sensible heat flow -155.30 W/m^2 and total heat flow 35.76 W/m^2, indicating a good agreement. The total heat flow is within 1% and the components are within 4%. This indicates that the total heat flow is well correlated between the Gibson method and the dynamic solver, but the amount of moisture evaporated is somewhat less accurate.

The above is for the wet surface, with implied wetness fraction of 1. Where wetness fraction is less than 1, the approach in the steady-state case is to effectively model two separate rock temperature distributions, one for the dry portion of the wall, the other for the wet portion (McPherson, 1993, section 16.2.3). This is a surprising path to take; the other option is to simply apply the wetness fraction as a factor on the latent heat component and then calculate the entirety of the wall as wet. Doing this, the equation for the sensible heat flow would remain unchanged, while the equation for the latent heat would become

$$q_L = w_f \frac{0.0007 h_c L_{ws} (e_{ws} - e)}{P} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

where w_f is the wetness fraction, and then no calculation would be required for the dry portion of the wall. This would be more consistent as well with the azimuthal symmetry of the radial heat transfer model. As is, in the current example, the temperature on the rock surface is 26°C on the dry portion and 18°C on the wet portion.

Changing the approach would result in different wetness fractions after calibration, but this isn't necessarily a problem, since the wetness fraction, as discussed, is already a parameter without a firm basis, accounting for multiple physical characteristics. And one that practitioners are already calibrating against observation.

It would also be the preferable option for the dynamic heat solver because we do not want to simulate two separate rock heat distributions, effectively doubling the computation for an already computationally expensive method. Therefore, figure 2 below shows a comparison of the 2 methods for the example above, across the wetness fraction range; the methods have been labelled the split method, for the separate dry and wet wall portions, and the single method, for the wetness fraction applied directly to the latent heat flow. For $0 > w_f < 1$, the single method calculates a latent heat flow greater than that returned for the split method. One way to be able to use the single method and have a result consistent with the split method (and avoid having to change the application of the wetness fraction) is to apply a correction factor to the single method. For this case, the correction factor is plotted in the second graph of figure 2. Applying this correction factor to the wetness fraction in the single method returns the same result as the split method.

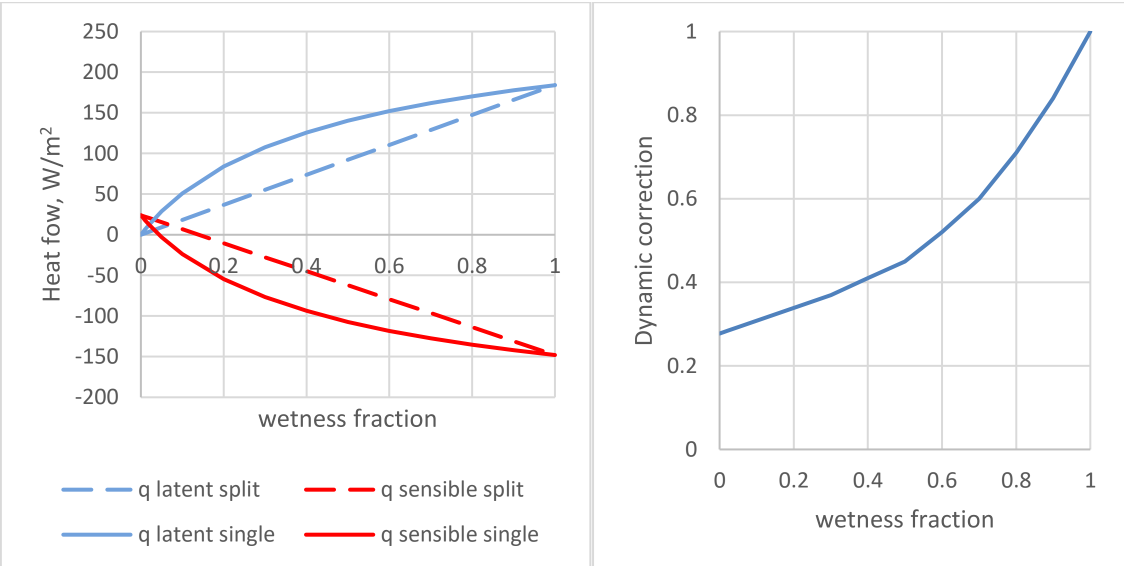

Figure 2 At left, a comparison of the existing split method for wet and dry walls to the single method, applying the wetness fraction directly as a factor to the latent heat flow; at right, the correction to the wetness fraction required to align the single method to the split method, for the case example presented.

The results for figure 2 are for the example presented; other examples have been tested showing the same correction factor applies for different VRT's, for different rock properties and for airflows. However, it does seem to depend on air temperatures, but not strongly. Further work could try to ascertain how to adjust the correction factor for different air temperatures (or air temperature differences).

The other option is to fully adopt the single method for all heat simulations, thereby redefining the wetness fraction. Table 1 presents the default wetness fractions from the Ventsim DESIGN wetness fraction presets, alongside what would be the approximate wetness fractions to use with the single method to return the same result when used with the split method, thereby providing a mapping between the 2 methods. Applying this mapping to a heat simulation using the single method would return approximately the same result, which is acceptable, as this is a parameter needing to be tuned by the practitioner regardless.

Table 1 Approximate mappings for wetness fraction between the split (current practice for steady state geothermal heat transfer) and single methods

Description	Split	Single
Very dry	0.01	0.003
Dry	0.10	0.03
Mostly Dry	0.15	0.05
Partially Damp	0.25	0.09
Damp	0.30	0.11
Partially Wet	0.40	0.16
Wet	0.60	0.31
Very Wet	0.80	0.57
Saturated	1.00	1.00

Something to be considered as well is whether the wetness fraction should be applied at all in situations of condensation (where the airway wet bulb temperature is greater than the wet surface temperature). In such cases, the water source is the air, which is available around the entirety of the tunnel perimeter, so wetness fraction could be set to 1. This would create a discontinuity around $q_L = 0$ that would need to be handled in any solver.

Additional further work could be done on determining which type of variation of latent heat flow with wetness fraction should be reasonably expected: the linear variation of the split method, or the seemingly asymptotic variation of the single method.

In summary, the advantages of the single method over the existing split method for applying wetness fraction are:

- Requires half the computation, which is critical for the computationally intensive dynamic heat solver,
- Respects the symmetry of the heat model; the split method introduces a sharp azimuthal variation to the model for $0 > w_f < 1$ which is unaccounted for in the 1D heat conduction and the 1D heat convection equations. This means that any unknown azimuthal effects are included in any calibrated wetness fraction using this method. Removing this sort of inconsistency in a method is a good thing to do and will help anyone investigating this topic in the future in ways that are not currently imagined. Perhaps someone does want to properly model azimuthal variation in the conduction, then they would start from the well-defined 1D radial model first.
- By applying the wetness fraction only to the latent heat flow equation, tightens the definition of the wetness fraction from:
    - the uniformly wetted surface area as a fraction of the total surface area that would give the same rates of heat and moisture transfer as the actual surface of non-uniform wetness,

  to the following:

    - the actual moisture evaporation in a tunnel as a fraction of the maximum possible moisture evaporation for a fully and uniformly wet tunnel.

Such a definition is more straightforwardly applied in the equation for latent heat transfer and allows the wetness fraction to be representative of different forms of wetness coverage and concentration in a tunnel while removing it from the notion of some proportion of uniformly wet wall. This may improve its applicability between different cases and provide a sounder basis for any further work on the topic in the future and in establishing useful and confidently applicable default values. For example, a wetness fraction for a case of dry walls and sodden floor, or dry wall with exposed side channel flow, or dry wall with intermittent high flow rate fissure water. This is something that remains to be seen, ideally from further investigation of calibrated wetness fractions.

6 CONCLUSIONS

The paper has reviewed a commonly used method of handling geothermal latent heat transfer and reviewed its limitations and implications. The lack of a well-defined physical basis for the wetness fraction – the key parameter in setting the geothermal latent heat flow – has been explored, highlighting the need for calibration, where possible, with observed temperature data. The application of the current method of geothermal latent heat flow for the dynamic heat throws up some difficulties and questions, particularly around the splitting of the wall into dry and wet sections. Some alternatives on the way forward exist. Either the existing definition of wetness fraction can be adjusted to fit when used in the dynamic context, or the wetness fraction could be redefined and used throughout in the manner described for the single method. The proposed single method has a simpler definition and application and agrees better with the symmetry of the rest of the geothermal heat model.

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