

EFFECTIVE MASS TRANSFER COEFFICIENT FROM THE MARTIAN REGOLITH .

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Introduction: The cycle of water on Mars has received increased interest from researchers, especially after recent evidence of abundant water in regions outside the polar caps. The upcoming Phoenix Mars lander, a NASA scout mission led by Peter Smith from University of Arizona, will land during the local summer in a region in the northern plains, where ice-cemented ground is expected to exist underneath a layer of dry regolith, to study the history and the cycle of water.

In preparation for the analysis and interpretation of the data expected from Phoenix, we are looking for simplifications in our model of water vapour mass transfer that may be useful to reduce the complexity of the simulations. In this study, the three dimensional steady state water vapour diffusion through the Martian regolith is considered, based on Fick's law of diffusion corrected for porous media and combined with turbulent transport in the atmosphere. The results of the numerical simulation of diffusion in the regolith for different atmospheric conditions on the surface are summarized by means of the Sherwood number. The Sherwood number, which can be seen as a nondimensional rate of diffusion normalized by a characteristic rate of diffusion calculated with a linear profile, is useful for researchers that require the water vapour flux from the regolith to the atmosphere, but do not want to calculate the complete mass concentration profile in the regolith and the near surface region. With the Sherwood number defined for a particular case, the water vapour flux from the regolith can be readily calculated given water vapour mass concentrations at two points, one inside the regolith and one at the near surface atmosphere, and the characteristic distance between these points. While we consider here various cases of different wind speed, results are shown only for two depths of the ice table.

Study of Water Transport on Mars: After the discovery of various evidences of abundant water on Mars, especially in the north polar region, the study of water transport on this planet has been pursued with great interest, with special focus on the history of water on Mars, its possible cycle on the planet and the forms of its existence and transport. There has been various studies on water transport in the atmosphere, from the regolith to the atmosphere, global water cycles, and effect of different phenomena on the water transport on Mars.

The complete physics of water transport on Mars involves numerous extensive subjects (e.g. multi-component mass transport, porous media, gas dynamics, diffusion, atmospheric physics), therefore, it would require large resources and time to include all the necessary physical processes in a model, while one may only

be interested in certain aspects of this model and not want to concentrate on the other complexities. The main goal of this paper is to determine a Sherwood number for the mass transport of water vapour from the regolith under different atmospheric conditions on the regolith surface. The water mass flux from the ice table to the surface is mainly by diffusion through the regolith, and it is proportional to the water mass concentration gradient in the regolith and can be influenced by atmospheric conditions and many other factors (e.g. nature of the regolith, pressure and temperature gradients). The water concentration profile is in general non-linear and different flow types and regimes on the surface influence the concentration gradient and change its profile. It would be convenient to determine a multiplication factor that includes the non-linear effects, so that the total water flux can easily be calculated assuming a linear profile, i.e. by knowing only the mass concentration at two points. The Sherwood number is a non-dimensional number that fulfills exactly this role.

Some preliminary information about the planet determines the main assumptions of our model and since our main interest is in the north polar region, we will mostly adapt the quantities that are reported to exist in this area. As for the general atmospheric conditions, the Martian atmosphere is dusty and is composed mainly of CO₂ (95.3%) with very little water vapour, on average approximately 0.03%. Although the amount of water vapour in the atmosphere is very small, abundant water vapour concentration on the northern polar region on Mars in the regolith near the surface along with ice-fogs are known to exist[1] and atmospheric column values of up to 76 ppt μm have been reported in this area[2]. In some transport models on Mars, water vapour was considered to be homogeneously distributed in the atmosphere, whereas Savijarvi[1] provides profile values based on a planetary boundary layer model, which will be used in our calculations.

The atmospheric pressure at zero ground level on the surface is approximately 600 Pa and temperature on the regolith surface is between 133 K to 300 K with an average of approximately 210 K [3]. For low regolith depths, it is assumed that a constant average temperature and pressure are acceptable and, for the conditions mentioned above, water exists in its solid or vapour state only. Ultimately, water vapour transport will be in a CO₂ abundant regolith.

The Martian regolith is composed mainly of dusty basaltic material [4, 5], hence, it completely falls under the definition of porous media. From previous studies on the Martian surface and soil characteristics, a shallow layer of dust with basalt type property is known to exist

in most areas of Mars. From thermal infrared spectrometry readings, this layer is almost entirely composed of fine grain material[6--9]. Also the estimated thermal conductivity from most of the Martian surface matches that of dry, sand like, material with medium to coarse particle size (approximately 500 μm)[10, 11]. For the dusty basaltic material, regolith properties have been estimated in numerous studies using various techniques and approaches. Important to us in this study is the approximate porosity and permeability of the northern regolith. In general, the porosity of the near surface is not well known. Porosities of $54 \pm 6\%$ and $36 \pm 16\%$ for silicate grain density of 2.5 g/cm^2 correspond to estimated densities at the Viking site[12]. Considering these data, we have assumed a 30% porosity and 10^{-8} m^2 permeability for the porous regolith domain in our model.

Physical model: The underlying physics of the water vapour transport in the Martian regolith consists of the generic mass and momentum transport equations applied to a binary vapour system in a porous medium. The main assumptions of this model are that the continuum mechanics applies (despite the very low pressure and temperature on Mars), the process is steady state, the transport mechanism is isothermal¹ and isobaric, since the pressure gradient over the regolith depth considered here is negligible. The velocities for the vapour components in the regolith (water vapour and CO_2) as well as the mass average velocity is negligible and the transport is considered to be dominantly diffusive. The system of equations for the vapour mixture present in the regolith is closed with a mass conservation equation for the water vapour mass concentration. Furthermore, corrections to the equations are done to include the effects of the porous medium. The main transport equations for mass and momentum conservation are:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \vec{\nabla}) \mathbf{u} \right] = -\vec{\nabla} P + \mu \nabla^2 \mathbf{u} \quad (2)$$

For the water vapour mass concentration the corresponding transport equation is:

$$\rho \left[\frac{\partial \omega_\alpha}{\partial t} + \mathbf{u} \cdot \vec{\nabla} \omega_\alpha \right] = \vec{\nabla} \cdot (\rho D_{\alpha\beta} \vec{\nabla} \omega_\alpha) \quad (3)$$

where $\omega_\alpha \equiv \frac{\rho_\alpha}{\rho}$ is the mass fraction and $D_{\alpha\beta}$ is the binary diffusivity. To include the effect of a porous medium, which acts as a resistance to the general transport, the material properties porosity and tortuosity

¹In general, this is not the case on the Martian surface and in the regolith since temperature gradients are significant and should be considered in the transport equations.

should be taken into account in the transport equations. The widely used form of the transport equations in a porous medium is:

$$\frac{\partial \varphi \rho_\alpha}{\partial t} + \nabla \cdot (\varphi \rho_\alpha \mathbf{u}) = \nabla \cdot \left[\rho \varphi \tau D_{\alpha\beta} \nabla \left(\frac{\rho_\alpha}{\rho} \right) \right] + S_i \quad (4)$$

where φ is porosity, τ is tortuosity and S_i is the momentum source term defined as:

$$S_i = -\frac{\mu}{\varphi K} u_i - c_F K^{-1/2} \varphi^{-2} \rho u_i \mathbf{u} \quad (5)$$

with K being the permeability, and c_F an empirical loss coefficient.

Numerical Model: In our study, we use the ANSYS/CFX10 second order finite volume software to solve the transport equations. To simulate water vapour diffusion in the regolith, a domain with both a porous region and pure fluid region is considered. The shape of the domain is a cube which is divided into two parts, a top part representing the atmosphere and a bottom part representing the regolith. The cube is 6 m long, and a height of 3 m for the atmosphere and a total thickness of 1 m. The regolith's depth considered in this study were 0.5 m and 1 m. This cubic domain was discretized using unstructured grid with a total of 95647 nodes. An area refinement was applied using inflated layers at the atmosphere-regolith interface with a first layer thickness of 0.01 m. The primary fluid in the domain is constant property CO_2 gas with density and viscosity calculated at the simulation temperature and pressure. In calculating viscosity for CO_2 , we used the following temperature-based function[13]:

$$\eta_{\text{CO}_2} = A + BT + CT^2 \quad (6)$$

where $A=11.336$, $B=4.9918 \cdot 10^{-1}$ and $C=-1.0876 \cdot 10^{-4}$ for CO_2 and is valid for temperatures $195 \text{ K} < T < 1500 \text{ K}$.

We assume the transport to be nonbuoyant. Temperature and the reference pressure are constant in the domain and are set at $T=230 \text{ K}$ and $P_{ref}=700 \text{ Pa}$, corresponding to the Martian values expected at the Phoenix landing site. To simulate turbulence in this study, we use the $k - \varepsilon$ model. The $k - \varepsilon$ model enables us to include the turbulent effects without requiring detailed information about the flow other than the velocity and turbulence kinetic energy profile. To include the effects of a porous medium discussed before, two parameters are set for the regolith, a volume porosity of 0.3 and permeability of 10^{-8} m^2 , corresponding to average values in the literature, as shown above. Boundary conditions are inlet with prescribed velocity and turbulence intensity profiles and water concentration. Intensity is calculated using the velocity magnitude and turbulence kinetic energy at each point.

Average velocity and turbulence kinetic energy were obtained from a 1D Martian Planetary Boundary Layer

dynamics model with E-1 turbulence closure scheme[14] for the geostrophic winds $|U_g| = 5, 10, 20, 35$ m/s. Since profile data were available at only six data points for velocity and turbulence kinetic energy, for our inlet profile we interpolated these data with the Akima polynomial procedure[15] to obtain 60 data points, required by the code for smooth boundary conditions. The U -velocity profile (horizontal wind) for a 10 m/s free stream wind velocity is shown in Fig. 1.

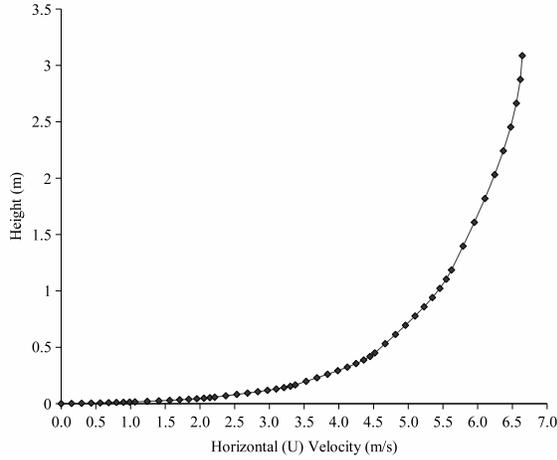


Figure 1: Example of interpolated velocity profile at the domain boundary (case of 10 m/s free stream velocity).

At the top surface of the atmosphere and the bottom of the regolith, we have applied a free slip wall boundary with prescribed water vapour concentration. We assumed 100% relative humidity at the regolith bottom boundary, which is 0.08523 kg/m^3 at 230 K (simulation temperature), to represent the saturation state at the top of the ice table. At the top atmosphere boundary, we have scaled the boundary layer concentration found by Savijarvi[1] to a column of 50 ppt μm water vapour, which resulted in $6 \cdot 10^{-4} (\text{kg H}_2\text{O})/(\text{kg CO}_2)$. In order to have the water vapour concentration in terms of density, assuming an ideal gas CO_2 at $T=230 \text{ K}$ and $P=700 \text{ Pa}$ with a density of $\rho_{\text{CO}_2} = 0.00104 \text{ kg/m}^3$, give for top domain boundary $\rho_{\text{H}_2\text{O}} \simeq 6 \cdot 10^{-7} \text{ kg/m}^3$. Furthermore, a zero relative average static pressure is set at the outlet, conservative interface flux at the atmosphere-regolith interface and symmetry boundary condition at the sides. The diffusivity in the additional transport equation for water vapour is calculated by using the gaseous binary diffusion coefficient of water into CO_2 at a reference temperature and pressure and then modifying it for the simulation temperature and pressure[16]. The reference diffusivity and the correction formula and factors are:

$$D = D_0 \left(\frac{T}{T_0} \right)^m \frac{P_0}{P} \quad (7)$$

where $D_0 = 0.1387 \text{ cm}^2/\text{s}$, $T_0 = 273 \text{ K}$, $P_0 = 1 \text{ atm}$ and $m = 2.0$. For $T=230 \text{ K}$ and $P=700 \text{ Pa}$, eq. (7) gives $D=14.25 \cdot 10^{-4} \text{ m}^2/\text{s}$.

The resulting set of equations is calculated until all the variables converge with a residual mean square below 10^{-5} as the convergence criteria.

Results and Discussion: From the results, a Sherwood number unique to each case is calculated. The Sherwood number is originally defined as:

$$\text{Sh} = \frac{k l_0}{D_{\text{eff}}} \quad (8)$$

where k is the mass transfer coefficient, D_{eff} is the effective diffusivity and l_0 is a characteristic length. We assume $l_0 = \Delta L$, which is the distance between the two known water vapour concentrations at the ice table and at 1.5 m height for a linearized profile. The Sherwood number could also be defined as:

$$\text{Sh} = \frac{D_{\text{eff}} \left. \frac{\partial \rho_w}{\partial z} \right|_{\text{reg}}}{D_{\text{eff}} \frac{\Delta \rho_w}{\Delta L}} \quad (9)$$

which shows that Sh can be calculated by dividing the vertical mass flux calculated inside the regolith by the characteristic linear profile. This was the method employed in the current study. To calculate $\left. \frac{\partial \rho_w}{\partial z} \right|_{\text{reg}}$ for each simulation case, we calculate the water vapour density gradient in the z (height) direction, averaged over a horizontal surface in the regolith at a depth of one half the ice table depth.

The characteristic lengths considered were $\Delta L=2.5, 2.0 \text{ m}$ for the ice table depth of 1 and 0.5 m, respectively. The concentration values used as described above resulted in $\Delta \rho_w \simeq 0.08523 \text{ kg/m}^3$.

The resulting values of Sh are shown in Fig. 2.

These results show that by having the Sherwood number calculated for different Mars conditions, one can easily obtain the net water flux to the atmosphere from the regolith by having the water vapour concentrations at known locations. This procedure is analogous to obtaining the overall heat transfer coefficient when heat flux needs to be calculated by having only two temperatures at two points.

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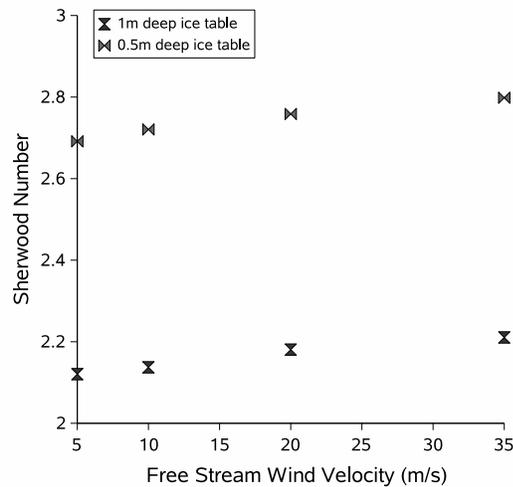


Figure 2: Sherwood number as a function of the wind speed for 2 ice table depths.

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