Synopsis

Name: Navneet Kumar
Degree: Ph.D.
Department: Mechanical Engineering, IISc, Bangalore
Thesis title: Evaporation of water from soil-like, leaf-like surfaces and unconventional porous media.

Evaporation is one of the inherent processes of our planet earth as an ecosystem. Water bodies, earth's surface and vegetation all contribute significantly towards the total evaporation which eventually leads to the formation of clouds. The physical processes governing the evaporation from these surfaces differ significantly and thus needs to be studied individually. The factors which affect the total evaporation (evaporation & transpiration) are the surface temperature, ambient temperature, relative humidity, external wind speed, pressure, surface area and geometry.

The present investigation deals with evaporation from three different surfaces: open water bodies, soil-like surfaces, and leaf-like surfaces. A ceramic infrared heater (2kW, 230V) has been used as the heater, in order to mimic the natural process, in all the experiments which were conducted in quiescent atmosphere i.e. without any external wind. The present work has been broadly categorized into two parts: - (a) evaporation from bare water surface, and (b) evaporation from a porous media. In part (a), we present experimental results on the evaporation from a bare water surface heated either from above using the infrared radiations or from below using heater immersed in the water. Heating from below leads to unstable stratification while infrared heating from above leads to stable stratification. The effect of water-side convection on the evaporation from a bare water surface has been investigated and all the experimental results have been combined to obtain a power law relation between Sherwood number (Sh) and Rayleigh number (Ra). Part (b) of the thesis has been furthur split into three major categories: - (1) evaporation from spheres based conventional porous media; (2) evaporation from novel porous media; and (3) evaporation from leaf-like surfaces.

Mono-disperse spheres-based (non-hygroscopic) conventional porous media are used to mimic the natural soils. Glass beads (0.10-0.16 mm to 2.5-3.0 mm diameter), Stainless steel balls (1 mm diameter), sieved natural sand (0.3-0.5 mm diameter) and hydrophobic Ball Grid Array balls (0.30; 0.50; 0.76 mm diameter) have been used to create the conventional porous media. The range of Bond number (Bo) spanned in the present investigation is $2.2 * 10^{-4} - 1.2 * 10^{-1}$ based on the spheres dimensions. The experiments were conducted either in a cylindrical vessel (63 mm diameter and 90 mm height) or in rectangular acrylic boxes having dimensions similar to that of the cylindrical vessel. The heat flux received by the top surface of the porous media in majority of the experiments was $1000 W/m^2$ which is close to the average annual solar insolation on the earths' surface. The evaporation from these soil-type surfaces was found to undergo different and distinct stages. In the 1st stage of evaporation, commonly known as the constant rate period (CRP) regime, where the water in a confined 3D porous media remains on the surface and a high evaporation rate is observed. Surface tension-driven formations of capillary film(s) which rise to the surface are seen during CRP. The strength of the capillary has been defined in terms of a characteristic length called the capillary break-up length. In the 2nd stage of evaporation often called a falling rate period (FRP) regime, the capillary film which was supplying water to the top surface of the porous media breaks-up. The break-up, also termed as the transition regime, leads to receding liquid-vapour menisci and heat is conducted through the top dried layer to the water below where evaporation takes place the evaporation rate drops. Along with the wetting properties, the spheres size has been found to effect capillary break-up length and hence the duration of the stages of evaporation drastically. Surface images captured using a thermal camera clearly showed the presence of water till the capillary break-up length. The capillary break-up length was also found to be affected significantly by the heat flux or in other sense we can say that the evaporation rate in CRP regime is critical in deciding its duration in a spheres-based conventional porous media. In the present investigation heat flux ranged from 250-2000W/m^2. Visualization has been carried out using a solution of de-ionized water and fluorescein dye. The colour contrast property (orange if dry and green in the solution form) of the fluorescein particles has been used to observe the evaporation sites in the porous media and to differentiate between the 1^{st} and 2^{nd} stage of evaporation. Apart from the experimental findings of single stack of mono-disperse spheres, multiple layering have also been investigated. The presence of complicated network of textural layering in the earth's surface is a well-known fact. Along with the preferential evaporation, evaporation enhancement & suppression are reported in the experiments with texturally layered porous media independent of the orientation viz. vertical or horizontal layering. The stacking positions are also found to be critical in determining the overall evaporation characteristics.

The geometry of a pore between three spheres in mutual contact is complicated. A simpler geometry for a pore could be that between two rods/plates in contact or three rods in mutual contact or stacks of either of these two. We call these types of porous media as "Novel porous media" as they possess many unique features not seen in a conventional porous media consisting of spheres. For this class of experiments the materials used to create the novel porous media were: Glass rods (2 & 3 mm diameter and 75 mm length), Glass capillaries (1.1/1.5 mm and 75 mm length), Faber-Castell pencil leads (0.7 mm diameter and 75 mm length), Glass plates (cross sectional dimension of 42 mm x 102 mm and thickness of 1.85 mm) and Cover slips (cross sectional dimension of 22 mm x 60 mm and thickness of 0.130.16 mm). The evaporation characteristics of vertically stacked rod-based novel porous media was found to be dominated by the corner films present in the near-zero radii contacts. Unlike the conventional porous media, the capillary break-up in the vertically stacked rod-based novel porous media was found to be limited by the vertical extent of the rods and not on the rod diameter. Due to the same reason, capillary break-up of vertically stacked rod-based novel porous media was also found to be independent of the heat flux range investigated in the present work. The 2^{nd} stage of evaporation in these types of novel porous media therefore does not hold the true meaning as it is not forced by the porous media. The effect of orientation has also been investigated and the surface roughness was found to affect the evaporation dynamics drastically in horizontally stacked rod-based novel porous media. However, it is the surface roughness which was found to be dominant in case of vertically stacked plate-based novel porous media.

The average size of a stoma, tiny holes present on the leaves, is nearly 20μm and the population density in majority of the plants is close to 5% of the leaf area. However the higher transpiration rates (60-70 % compared to a bare water source) sustained by a plant has remained a mystery for the phytologists. To study this we mimic the leaf-type surfaces by manufacturing silicon wafers having through holes. The leaf-mimics had different hole-diameter but same open area.

The leaf-mimic with the smallest hole-size was found to evaporate the most while with increasing the hole-size the evaporation was found to decrease. In all the types of the leaf-mimic the evaporation ratio (ratio of the evaporation rate from the leaf mimic to that of the evaporation rate of a bare water surface at the same surface temperature) was found to increase with decreasing heat fluxes. The 3D nature of diffusion near these tiny holes enhances the evaporative flux, owing to increase in the concentration gradient of water vapour, which explains the high evaporation rates observed in the present work.