

## Introduction

### Motivation

Combined heat and mass transfer in hygroscopic porous solids occurs in many engineering applications. The drying of biological and chemical products and the dehumidification of gases by the use of adsorbents like Silicagel are some of the important examples to mention.

The present study arose in connection with the general problem of packed beds of hygroscopic material subjected to through air flow. Theoretical solutions to this problem, available in the literature, are largely based on the assumption of local hygroscopic equilibrium between the bed material and the adjacent air. The interaction of bed particles under non-equilibrium conditions with the surrounding air may be understood by considering the combined heat and mass transfer from a small sphere of the bed material exposed to varying states of air. This requires that the effects of actual shape of the bed particles and contacts between them may be ignored.

### Theoretical Work

A literature survey of the mathematical models for the combined heat and mass transfer in porous sorbent solids has been made. In the present work, governing transport equations are set up by considering the moisture transfer within the porous sorbent to be given by the sum of two separate fluxes of Fickian diffusion type, based on the gradients of sorbent

pore humidity and moisture content respectively. The former of these fluxes is to represent moisture transfer occurring in the pore fluid, and the latter moisture transfer within the sorbent other than that which occurs within the pore fluid. The heat transfer flux within the sorbent is based on an effective thermal conductivity. The heat and mass transfer at the sorbent surface exposed to air are considered to be given by appropriate film transfer coefficients. Solutions for the above mathematical model have been obtained as under:

(a) Analogy Solution : Following Henry (57), and Close and Banks (45,47,49), the condition is established for obtaining uncoupled differential equations and corresponding boundary conditions in terms of combined potentials, with the equations and boundary conditions being analogous to those of heat transfer alone. Thus, for the special cases where these conditions are satisfied, solutions of the heat transfer available in the literature may readily be used to obtain the solution to the problem under consideration.

(b) Analytical Solution for linearised equations for the specific case of a sorbent sphere : Analytical Solution for the case of a sorbent sphere in initial equilibrium conditions and exposed to sudden and constant rate changes in surrounding air state are obtained for linearised form of the governing equations using the Laplace Transform technique. These solutions are applicable where the conditions for



analogy solution may not be satisfied. Approximate analytical solution is also possible for arbitrarily varying air state by considering the superposition of a series of sudden and constant rate changes in air state, the latter approximating the actual air state change.

The state path, on psychrometric chart, of the pore fluid in the sorbent sphere at various radii, immediately following a sudden change in air state is examined. Also the limiting values of lumped heat and mass transfer coefficients following sudden and constant rate changes in air state are obtained analytically.

Typical theoretical results for a sorbent sphere based on the linearised model are presented in appropriate dimensionless parameters.

(c) Numerical Solutions for the specific case of a sorbent sphere : The non-linear coupled partial differential equations and the corresponding boundary conditions have been numerically solved in the case of a sorbent sphere, by using finite difference equations for the spatial derivatives and by the use of Milnes' predictor-corrector method (81). A suitable computer programme has been developed. The solutions obtained by the numerical method and the analytical method have been compared for typical property values.

### Experimental work

The above theoretical solutions for a sorbent sphere are based on the assumption that simple diffusional type processes exist within the sorbent. There are conflicting evidences reported in the literature. Further, the following assumptions have also been made:

- i) Equilibrium of infinitesimal parts of the sorbent sphere with the adjacent pore fluid.
- ii) Uniform film transfer coefficients on the surface of the sorbent sphere.
- iii) No dimensional changes in the sphere.
- iv) Absence of sorption hysteresis.

In view of these assumptions, it is necessary to experimentally study the transient heat and moisture transfers within sorbent spheres to verify the postulated theoretical model. For this purpose, drying experiments are conducted by exposing a single layer of nearly spherical beads of Activated Alumina, having a mean diameter of 6 mm, and placed just above the bed of the same material, to the air passing through the bed and issuing out of it. A layer of glass spheres, 5 mm in diameter are kept on top of the single layer of Alumina beads to simulate flow conditions on the down stream side. The test layer is made up of (i) a central circular part, 100 mm diameter, which serves as a weighing pan, being independently suspended from an Analytical balance; and (ii) an annular guard ring of 210 mm

diameter with a clearance space of 5 mm from the central circular pan. The bed and the test layer are kept in a well insulated cylindrical test chamber.

An air supply system for delivering steadily, controlled state of air to the test chamber in the range of 10C to 60C dry bulb temperature, and 2 C to 35 C dew point temperature has been developed. A special type of air saturator developed at the Mechanical Engineering Division, CSIRO, Melbourne, Australia, is utilised for dew-point temperature control. The bed and the single layer of particles are allowed to attain equilibrium for several hours with a particular state of air and then the state of air is changed to a different condition. The change in mass of the central part of the test layer is measured while the sorbent attains new equilibrium condition. The state of air issuing from the bed is measured by a specially designed psychrometer. Tests are conducted with different air velocities, states and with different bed depths, including no bed.

The two diffusion coefficients for the moisture transfer within the sorbent are obtained by a procedure of curve fitting the theoretical overall moisture content variation with time, with the corresponding experimentally determined variation for the case where the air state changes nearly suddenly. For this purpose, the theoretical determination of the overall moisture content variation with time, is based on the analytical solutions derived in the present work, for the linearised model of the governing equations. In obtaining these theoretical

results, all the required equilibrium properties are determined, using appropriate thermodynamic relations, from the experimentally determined adsorption isotherms of the Activated Alumina, at the temperatures of 25.14 C and 33.48 C. The specific heat of dry solid, apparent and true densities, and porosity of the Activated Alumina, are obtained from manufacturer's catalogue. The surface film transfer coefficients for the sphere and the thermal conductivity of Alumina are obtained from the literature.

Although the comparison of theoretical and experimental relations between the overall moisture content and time, for the case of Activated Alumina, indicated a definite relation amongst the two moisture diffusion coefficients postulated, it failed to yield any unique values for these. However in the present work with Activated Alumina, the diffusion coefficient representing moisture flux in the pore space is determined by assuming that the diffusion coefficient representing the moisture flux in the sorbed phase is zero. These transport properties are then utilised to compare the theoretical with the experimentally determined moisture content variation with time for gradual change in air state and also for sudden change in air state for different ratios of the step changes in temperature and humidity ratio. It is concluded that the mathematical model used gives fairly good agreement with the experimental values in the case of Activated Alumina, which is used in the experiments.