SYNOPSIS

The excess of energy demand over its availability in conventional form is causing energy crisis all over the world and it becomes necessary to search for new sources of energy. It is apparent that solar energy is an attractive alternative source to fulfil the energy deficiency because of its abundance in availability and non-pollutant in nature. Many investigators are carrying out intensive research on utilization of solar energy in all possible and feasible ways. Particular attention is being paid to solar heating and cooling systems for which the key component is the solar collector. For low to moderate temperature applications flat-plate solar collectors are commonly used to intercept solar irradiance. Several studies, theoretical as well as experimental, on flat-plate collectors of various geometries are reported in the literature. One of the chief components of the flat-plate collector is the absorber plate whose primary function is to absorb as much incoming solar radiation as possible, to lose least possible heat and to transfer the retained heat to the energy transport fluid flowing through the passages which are integral with or fastened to it. Of all the geometries, the one consisting of the absorber plate with two parallel straight thin metal sheets forming a uniform channel for the working fluid has been studied by a number of investigators and is found to yield the best collection efficiency due to the fact that such a geometry provides maximum direct contact area of heated surface to the heat removal fluid.

In order to obtain better design characteristics for the best collection efficiency from the collector with absorber plate of the model described above, it is essential to analyse mathematically the heat transfer phenomena between the two parallel plates. But, many of the physical problems that we come across are not susceptible to exact solutions. In some cases, even if it is possible to obtain exact solutions with great or little effort, these solutions are so complicated that they are not amenable for easy computations for the physical interpretations of the solutions. In such cases one has to seek approximate methods yielding somewhat accurate solutions within the framework of approximations. It is a well established fact that the integral method serves the purpose of providing approximate solutions to a majority of problems of momentum, heat and mass transfer. Accordingly, the present work concerns with the studies of heat transfer in the parallel plate absorber of a flat-plate solar collector, when the lower plate is thermally insulated and the upper plate is exposed to the sun, by using integral method and examining its accuracy by comparing the results with the exact solutions whenever possible. Further, considering the length of the channel to be far greater than its width and flow to be caused by an external agency or by thermosyphonic flow, the flow can be assumed to be fully developed. In addition, since the Reynolds numbers for the flow in the collector are of the order of a hundred, the flow can be taken to be laminar with a parabolic velocity profile, or with a uniform velocity profile for a flow with a greater degree of mixing and these two types of velocity profiles have been used throughout the present work.

This thesis comprises of four chapters of which Chapter I is introductory. Chapters II and III are concerned with steady state convective heat transfer and Chapter IV is devoted to the transient heat transfer. Furthermore, the case of upper wall being subjected to a prescribed heat flux has been considered in chapters II and IV, and the case of upper wall being subjected to a prescribed temperature has been examined in Chapter III. The behaviour of various physical quantities has been studied from the exact and approximate solutions in Chapters II and III, and from the approximate solutions in Chapter IV. The approximate method is the well-known integral method with the temperature profiles satisfying the essential boundary conditions.

Chapter I deals with literature survey on flat-plate solar collectors. This survey includes the discussion of various studies on : general performance characteristics of flat-plate solar collectors; selective surfaces; glazings and glazing materials; dirt effects; honeycomb collectors, evacuated collectors; flat-plate collectors augmented with planar reflector systems; geometries of the absorber plate and orientation of flow passages and convective heat transfer studies of flat-plate collectors. A brief discussion of the importance and limitations of Hottel-Whillier-Bliss equation is also given in this chapter.

Chapter II is devoted to the study of convective heat transfer for laminar flow in a parallel plate absorber when the upper wall is subjected to a prescribed heat flux. Assuming constant thermophysical properties of the fluid, negligible viscous dissipation and constant heat flux at the upper plate, the energy equation governing the temperature distribution in the channel has been solved using the method of separation of variables. When the velocity profile is uniform, the solution is obtained in terms of Fourier series. In the case of parabolic velocity profile the problem reduces to that of solving Sturm-Liouville differential equation which has been solved by employing series method and the solution is obtained in terms of confluent hypergeometric functions. By solving the resulting characteristic equation numerically using bisection method twenty-five eigenvalues and, consequently, the associated eigenfunctions and expansion coefficients have been determined. Due to the involvement of computational complexities in the determination of higher eigenvalues, asymptotic method has been developed to determine them. This method simplifies the characteristic equation and yields the eigenvalues

$$\lambda_n = 4n + \frac{1}{3}\,, \lambda_m = 4m + \frac{7}{3}\,, \quad m,n = 0,1,2,\ldots,$$

which are, indeed, very close to those obtained by the numerical method except when $n,m = 0,1$. The problem has also been solved using finite-difference method employing third and fifth order procedures. It is found that the fifth order procedure yields the eigenvalues of desired accuracy at a faster rate than the third order procedure.

Next, the approximate solutions of the problem adopting integral method with fourth degree polynomials as temperature profiles in thermally developing and fully developed regions have been obtained for the case when the heat losses from the upper plate to the surroundings are proportional to any non-dimensional power, n, of the difference of plate and ambient temperatures.

When the heat flux at the upper plate is constant, it is found that the thermal entrance length is directly proportional to the Peclet number, R. This implies that if the collector with a specified heat removal fluid is operated at high flowrates, the thermal entrance length is large and consequently the collector plate length should be considerably large. This suggests, from the view point of optimum dimensions of the collector, that the collector should be operated at moderately low flowrates. If it is desired to operate the system at fixed flowrates, then in order to achieve smaller thermal entrance lengths, the width of the channel should be small. However, in the case of air heaters the gap width can be considerably greater than that of water heaters. The Nusselt number of the upper plate in the very beginning of the thermal entrance section increases with R and declines steadily along the plate length in such a way that it approaches a limiting or fully developed value $\frac{70}{13} \doteq 5.385$ irrespective of the value of Peclet number.

The numerical results computed from exact and approximate solutions reveal that they differ quantitatively within a few percent only. It is found that fully developed solutions predicted by fourth degree polynomials as temperature profiles are very close to the exact ones, whereas those predicted with second degree polynomial temperature profiles deviate appreciably, as expected, from the exact ones. The fully developed Nusselt numbers predicted by fourth and second degree polynomials are 5.385 and 5.714, respectively, which show that the former value coincides with the exact value while the latter deviates by about 6 per cent from the exact value. This trend indicates that the choice of second degree polynomial is inadequate and this may be attributed to the fact that some of the essential boundary conditions are not satisfied by the second degree polynomials.

The collection efficiency, e, of the collector has been evaluated in terms of the dimensionless length of the plate for various values of the parameter, N_n , equal to the product of Peclet number, R, and the heat loss coefficient, h_n. It is found that e decreases as the plate length increases. The diminishing of e is weak for higher values of N_n. Further, it is observed that as N_n increases the efficiency decreases rapidly with the plate length.

Convective heat transfer for laminar flow in the parallel plate absorber when the upper plate is subjected to a specified temperature has been analysed in Chapter III by employing exact and approximate methods. When the velocity profile is parabolic and the upper plate temperature is constant, the energy equation in differential form has been solved and the solution is obtained in terms of confluent hypergeometric functions. The application of the asymptotic method yields the positive eigenvalues

$$\lambda_n = 2n - 1, \qquad n = 1,2, \ldots ,$$

which are in good agreement with those obtained numerically except when $n = 1,2$.

In order to find the approximate solutions, the energy equation has been taken in integral form and second, third and fourth degree polynomials satisfying appropriate boundary conditions were selected to represent temperature profiles in thermally developing and fully developed regions. Assuming the upper plate to be at a constant temperature, various physical quantities of interest, such as thermal boundary layer thickness, thermal entrance length, heat flux distribution and local Nusselt number of the upper plate and temperature distribution across the width of the channel have been determined.

From the exact method of analysis it is found that the Nusselt number of the upper plate approaches the fully developed value 4.861 when the velocity profile is parabolic and 4.935 in the case of uniform velocity distribution. Comparison of numerical values of various physical quantities obtained from exact analysis and those predicted by approximate analysis reveal that, in thermally developing region the results obtained using fourth degree polynomial and, in thermally developed region the results determined using third degree polynomial are within a few per cent of the exact ones, whereas the predictions based upon second degree polynomial deviate appreciably from the exact solutions. In fact, the predictions based on second degree polynomial temperature profiles can not be relied upon because these polynomials do not take care of all the essential boundary conditions.

The numerical results of heat flux distribution at the upper plate reveal that in the very beginning of the entrance section the heat flux reaching the fluid decreases significantly as Peclet number increases. This shows that when the mass flowrate is small, the heat removal fluid picks up more heat in the beginning of the thermal entrance section and less heat at distances far away from the inlet region. When the Peclet number is fixed, the heat flux into the fluid decreases with plate length. This implies that the collection efficiency decreases along the plate length. An important observation from the analyses of Chapters II and III is that the thermal entrance length when the upper plate is at constant temperature is about three-fourths of the corresponding value when the plate is at constant heat flux. Another important observation is that the fully developed Nusselt number in the case of constant temperature is nearly nine-tenths of the corresponding value of constant heat flux case.

The analyses presented in Chapters II and III assume the system to be in steady state conditions. But a knowledge of the transient response of a flat-plate solar collector is useful in assessing its performance during the initial heating (or cooling) period. This forms the subject of Chapter IV. Taking energy equation in integral form and fourth degree polynomials, satisfying all the essential boundary conditions, as temperature profiles the solutions have been obtained using the method of characteristics when the heat losses from the absorber plate vary as any non-dimensional power of the difference of plate and ambient temperatures.

From the numerical results it is observed that the thermal entrance length depends upon the choice of the velocity distribution and the Peclet number, whereas the time required to reach steady state conditions at this length is independent of the velocity distribution and Peclet number when the heat losses are negligible. Further, it is seen that for a selected working fluid the system takes longer times to reach steady state conditions when it is operated with lower mass flowrates. When the heat losses from the absorber plate vary with first and second powers of the difference of plate and ambient temperatures, it is found that in the initial heating period the heat losses from the plate are more, and as the transient proceeds the energy transport fluid picks up more heat so that the heat losses from the plate reduce considerably. Furthermore, it is observed that at initial heating period the effect of mass flowrate on thermal response of the wall is insignificant and affects the thermal response of the wall appreciably as transient advances.

Finally, the thesis concludes with an Appendix in which transient heat transfer for laminar forced convection in the thermal entrance region of a flat duct has been examined using integral method in conjunction with the method of characteristics. The results have been compared with those obtained by using finite-difference method and it has been found that the choice of the fourth degree polynomial satisfying all the essential boundary conditions seems to be more appropriate than the third degree polynomial.