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Review of 1983–1986 Chinese literature on heat transfer

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INTRODUCTION

As reported in a recent survey [1], heat transfer is one of the very active disciplines in technical science in China, especially since the degree system (Bachelor, Master and Doctor) was carried out in universities and institutes (January 1981). Heat transfer research is not only of great importance for improving energy conservation systems, but also may contribute to advances in material science and engineering, to improve high technologies in modern information systems, to push forward the bioengineering, and therefore to speed up the industrial and agricultural production in China.

The research activities in heat transfer in China are quite widespread and profound. There were more than 150 papers submitted to the annual nation-wide heat transfer conference sponsored by the Division on Heat and Mass Transfer of the Chinese Society of Engineering Thermophysics (CSETP) since 1980. The 1st and 2nd National Conferences on Engineering Thermophysics in Colleges and Universities were held in Nanjing and Wuhan, September 1983 and October 1986, respectively. The 1st Nationwide Thermophysical Property Conference was held in Dalian in October 1984. A nation-wide special symposium on thermal hydraulics and nuclear reactor safety was held in Xiamen in April 1984. Moreover, there were also a few papers on heat transfer presented at various symposiums held by the Chinese Mechanical Engineering Society (CMES), the Chinese Society of Chemical Engineering and Technology (CSChET), the Chinese Society of Aeronautics and Astronautics (CSAA), the Chinese Metals Society (CMS), the China Society of Measurements (CSM), the Chinese Solar Energy Society (CSES), etc. Such a large number of papers were written in Chinese without exception, and only a few of them were accepted for publication in journals or to be collected in bound volumes [2–4]. They therefore are seldom known to the foreign heat transfer communities.

It is quite difficult to make a comprehensive review of all the heat transfer papers written in Chinese, especially to cover many research reports and M.S. theses on heat and mass transfer published in Chinese universities and institutes. This review surveys only the papers that have been published in the Chinese open literature covering various fields of heat transfer during 1983–1986, so as to highlight areas of research during the past three years.

HEAT CONDUCTION

A new rigorous method on the conventional variable separation technique together with the finite element principle, was proposed to solve the transient heat conduction problem with random geometry and arbitrary time-dependent boundary conditions [5, 6], and was used successfully to predict the complex passive transient thermal environment in/around the underground cave for fruit preservation [7]. In order to get the actual thermophysical properties of soil for taking care of moisture migration, the principal measuring errors with a conventional probe were analysed [8], and a new manner, 'heating–cooling method', was developed to measure simultaneously the thermal diffusivity and conductivity of disperse media in the scene with a probe [9], both the temperature rises when the heater inside the probe is 'on' and the temperature drops when the heater is 'off' are to be recorded so as to calculate the property values.

A comprehensive analysis algorithm for ablation, temperature fields and thermal stresses of the carbon nose-tips were made public recently [10]. The measurement of the thermal conductivity for a charring ablation thermal protection material under transient heating was reported in ref. [11].

A regular perturbation solution was obtained for outward and partial inward spherical and cylindrical inverse Stefan problems [12, 13], and such perturbation solutions agreed well with numerical results.

Phase-change problems in one-dimensional slabs were solved by the method of matched asymptotic expansions [14]. An implicit numerical technique using cubic splines was presented in the variable time step method for a one-dimensional Stefan problem with mixed boundary conditions [15]. A theoretical analysis of heat conduction factors and experimental research on heat conduction properties for composite materials have also been presented [16].

A method of transformation was suggested to linearize the unsteady heat conduction problem with variable thermal properties [17].

A finite element method was presented for solving the inverse problem of heat conduction and its application to measure the thermophysical properties was shown and discussed [18].

A new equation for the thermal conductivity of liquid mixtures was proposed on the basis of Eyring's theory for viscosity of pure liquids and for heat conduction in dense gases, and was used to predict successfully the thermal conductivity of multicomponent liquid mixtures [19].

NATURAL CONVECTION

Application of the transient method to investigate natural convection across air layers at various angles of inclination was reported in ref. [20].

The laser double-mirror interferometer was used to measure the temperature field for natural convection near a flat plate of uniform temperature [21], while a holographic interferometer was used to study the free convection heat transfer for a horizontal cylinder [22], the results obtained compare well with those reported in the literature.

A numerical iterative method to solve a two-dimensional natural convection problem was presented in ref. [23]. The fluid temperature field for laminar natural convection in a horizontal annulus with some added solid materials was calculated by a numerical technique, which agreed well with the experimental results from holographic interferometry [24].

The external natural convection around three horizontal tubes in a vertical array was studied experimentally in ref. [25].

The phenomenon of frost formation on a vertical plate under natural convection was studied photographically in ref. [26].

FORCED CONVECTION WITHOUT PHASE CHANGE

The mechanism of the 'thermal drag' and 'thermal round-about' for flow of thermofluids was investigated both analytically and experimentally [27, 28], it reveals really a new methodology for treating the thermofluid flow phenomena. A new technique, 'double block correction', was suggested to speed up the convergence of the numerical calculation of heat transfer and fluid flow in ref. [29].

To verify the effectiveness of the heat and mass transfer analogy, naphthalene sublimation experiments of external flow across a single cylinder and internal duct flow were carried out on a suction-type wind tunnel [30], the results show that the maximum deviation of mass transfer data from the corresponding heat transfer correlation is within ±5.5%. The mass transfer for film flow of non-Newtonian power-law fluids were studied experimentally in ref. [31].

Investigation on heat transfer in the acute angle of triangular ducts was presented in ref. [32]. Flow visualization in a complex duct was reported in refs. [33, 34].

The dimensionless equation of heat convection and analysis on the effect of geometrical dimensions of a finned elliptic tube were presented in ref. [35].

The temperature distributions in the steady laminar wake behind a heated slender streamline body of revolution were measured and analysed in ref. [36].

TWO-PHASE FLOW AND HEAT TRANSFER

An analytical model was presented for saturated or subcooled laminar-flow film boiling, possibly for the first time in the literature to cover the effect of a pressure gradient caused by the increasing vapour film thickness along the flow direction [37–39]. It was found that this effect will be prominent for low-velocity laminar film boiling on a horizontal plate surface, especially for the case of a large ratio between the density of the liquid and that of the vapour. A physical model, hypothesizing a vapour–liquid mixing layer between the vapour film and the bulk liquid, and a semiempirical theory was developed for turbulent flow of subcooled liquid along a horizontal plate, the empirical values of two constants are determined through experimental investigation with subcooled deionized water [39, 40]. This semiempirical theory had been further advanced recently, such that only one empirical constant needs to be experimentally determined [41].

The conductance-probe technique was used to measure the time-averaged void fraction in the two-phase flow of an air–water mixture through a horizontal and vertical tube [42], and the research on characteristics of two-phase flow and heat transfer in helically-coiled tubes was reported in ref. [43]. The experimental results and its discussion on the flow pattern and deterioration of boiling heat transfer in the bend of a 25×2 mm vertical U-shaped tube with a radius of 700 mm under the conditions of $p = 45$–144 bar, $G = 3800$–2000 kg m^{-2} s^{-1} and $q = 80$–330 kW m^{-2} were reported systematically [44, 45].

Boiling on surfaces with artificial nucleation sites was studied experimentally and a comprehensive model was developed to predict the effect of cavity size and cavity density on boiling heat transfer [46–48].

An equivalent nucleate-boiling model for bubble growth on the wall, considering the effect of the relaxation microlayer beneath the bubble, was presented in ref. [49]. Analysis was made on the critical liquid level of boiling in a liquid film and checked well with the water experiments at atmospheric pressure [50].

The microstructure of flow, especially the Benard cells, inside evaporating liquid drops on a horizontal flat plate were discovered [51], a laser shadowgraphic method was used to investigate the interface structure, and a calculating procedure to evaluate the volume–time history of the sessible drops on a vertical plate [52]. Real-time grating shearing interferometry was developed to improve the flow visualizations and quantitative measurements [53], and the research work was recently extended to binary liquid drops [54].

Contact phenomena and heat transfer between the impinging liquid droplet and a hot surface were investigated, three different heat transfer mechanisms of such impingement were concluded [55]. The immersion cooling and jet impingement cooling of microelectronic chips were experimentally studied and a new hysteresis phenomenon was discovered [56].

A general correlation for predicting average heat transfer coefficients of film condensation was suggested and the results calculated by this correlation were reported to be in good agreement with the experimental data in the literature [57]. Investigation of laminar film condensation of pure steam inside a vertical elliptical tube both theoretically and experimentally was reported in ref. [58]. The laminar film condensation of an R113–air mixture on a vertical plate was studied, with the measurements of temperature distribution, component concentration and the diffusion boundary-layer thickness [59].

The heat transfer to a horizontal tube in the freeboard region of a fluidized bed has been investigated, it was suggested that different heat transfer correlations should be used for different zones [60]. Heat transfer between a gas–solid fluidized bed and wall surface has also been studied [61]. A method was proposed for measuring the particle heat transfer coefficient in a fluidized bed in ref. [62].

NUCLEAR REACTOR HEAT TRANSFER

An empirical correlation has been developed to cover the pressure effect on CHF (critical heat flux) in a square-array rod bundle with uniform heat flux, the experimental parameter ranges were: pressure, 80–150 atm; mass velocity, 4×10^6–12×10^6 kg m^{-2} h^{-1}; local quality at CHF point, -0.20 to 0.15 [63]. Rewetting heat transfer during bottom flooding of tubular and annular test section was investigated experimentally [64, 65], the rewetting velocity increased with back pressure. The results of the reflood experiments showed that the simultaneous top and bottom coolant injection may improve the cooling significantly for the same total flooding rate, as compared with the top or bottom injection alone [66].

A method was presented to calculate drag coefficients for spacer grids in bundles, the calculated values were in good agreement with corresponding experimental data [67]. A two-fluid model was used to analyse the thermal hydraulic transient process of reactor cores [68].

A new flow pattern map for a high-pressure steam–water system in horizontal pipes was deducted from model experiments carried out with R12 at 10–15 bar in ref. [69].

THERMAL RADIATION

A new type of blackbody model based on using a perfect hemispherical mirror was presented, which may be a useful tool for accurate determination of solar and other radiative fluxes [70]. A new scheme for measuring sky long-wave radiation and effective sky temperature was reported [71].

Simple expressions for calculating the emissivities of carbon dioxide and water vapour in a combustion chamber were obtained based on a combined-band model [72]. A simple and reliable transient technique for measuring the hemi-spherical emissivities of metal and coating was developed, of which the accuracy may be satisfactory for engineering practice [73].

The Monte-Carlo method for predicting radiative heat transfer was described in a simple way, with discussions on calculating results [74, 75]. A radiative heat transfer problem was solved by the net heat-flux method in ref. [76].

The cause of instability in a laser beam was analysed by using radiation combined with a conduction and convective heat transfer model [77]. Based on the integral equation of radiative heat transfer, an analysis of the heat flux distribution between a combustible porous hot plate with a 15° inclined grey cold plate was reported, the calculated results agreed well with the actual measured values [78].

HEAT AND MASS TRANSFER IN POROUS MEDIA

To meet the needs for energy saving with adaption of thermal insulation, the thermal conductivity and diffusivity of wet porous building materials were studied experimentally [79]. It was found that, the effect of moisture migration on thermal diffusivity will be somewhat strange in the range of small moisture content and a point of inflection appears on the curve of thermal diffusivity of aerocrets and standard sand vs moisture content [79, 80]. The complex phenomenon of heat and mass transfer in wet porous building materials was treated theoretically in ref. [81]. A new method for determining the mass diffusivity and 'mass thermal conductance' of moist porous media under the third kind of boundary condition was developed in refs. [82, 83].

The results of experimental research in pool boiling and boiling of the liquid layer from porous surfaces were reported in refs. [84, 85].

The free convection and radiative heat transfer from a flat plate with a thin layer of porous materials in front was analysed in ref. [86].

HIGH-TEMPERATURE HEAT TRANSFER AND PROTECTIVE COOLING

The effect of pressure on heat transfer to a particle exposed to a thermal plasma was shown to be caused mainly by the presence of a Knudsen effect for small particles with radii typical for application in plasma chemistry and plasma processing [87]. A computational study of heat transfer to a cylinder immersed in a thermal plasma crossflow was reported

[88], the results calculated agreed very well with Kanzawa–Nonouchi's experimental data (*Int. Chem. Engr* **16**(1), 184–189 (1976)).

Based on the experimental results, expressions for the anode heat flux were suggested for high-intensity cathode-jet dominated and anode-jet dominated arcs, respectively [89]. A theoretical and experimental study of the temperature and flow fields of a free-burning arc under a transverse magnetic field was presented in ref. [90].

An improved calculation method was suggested for evaluating flow field and heat transfer near the stagnation region of a turbine blade [91].

A lot of work has been done on the film cooling for protection of the material surface exposed to a high-temperature gas stream [92–95], and was recently summarized in a monograph 'Film Cooling' [96].

The concept of equivalent mass flow of flue gas was introduced for developing the film protection against a corrosion/erosion effect of impurities in flue gas as an analogy to ordinary film cooling [97].

HEAT TRANSFER IN COMBUSTION CHAMBER

The Monte-Carlo method was used to solve the radiative heat transfer problems of a cylindrical furnace taking into account the presence of convective heat transfer [98, 99]. The problems of the Monte-Carlo solution of radiative heat transfer in a furnace were discussed, and a revised method was developed to reduce the computing time and to raise the accuracy of computation [100].

A numerical computation was made to predict the flow field in a combustion chamber by the time approach method [101].

An investigation was done on the temperature distribution at the outlet of an annular combustor of a P-type turbojet engine [102]. A numerical simulation of two-phase flow by the random vortex method was reported [103]. Methods were proposed to calculate the wall temperature and heat flux in a gas-turbine combustion chamber [104].

CRYOGENIC HEAT TRANSFER

The effect of Kapitza thermal resistance exists in the phase-interface on cryogenic heat transfer. Experiments on the effect of Kapitza thermal resistance on heat transfer in a liquid bath were made, and a modification to Schmidt's equation (Workshop on Stability of Superconductors, IIR, 1982) was suggested to evaluate the boiling heat transfer in a liquid helium bath [105].

The condensation heat transfer of saturated N_2 vapour inside a V-shaped corrugated vertical tube was studied for 32, 36, and 40 grooves with the same tube diameter [106].

An analytical model was presented for the calculation of the heat transfer coefficient between a cell and an aqueous medium, an analysis was made to estimate the temperature difference across the membrane during freezing and its effect on the attendant water transport via thermoosmosis and other mechanisms [107].

ENHANCED HEAT TRANSFER

The research and applications on heat pipes, variable conductance heat pipes, thermosyphons and their various applications were carried out at the Chinese Academy of Space Technology and at the Chongqing University for more than ten years [108, 109]. Data correlations for the heat transfer of a large two-phase closed thermosyphon were reported [110]. A thermosyphon reboiler with a transparent film heating tube was investigated in ref. [111].

In order to find better types of tube inserts for augmentation of heat transfer of gas flow in the lower *Re* range, flow visualization by means of the hydrogen bubble technique and comparative tests of friction drag and heat transfer of air flow in a vertical tube with uniform temperature was made [112]. The heat transfer coefficient and power required for helical ribbon mixers were reported in ref. [113].

Experimental observations were made on enhanced heat transfer in fluids subjected to high frequency oscillations, which may be developed as a new effective technique [114].

Heat transfer augmentation and flow friction of perforated fin surfaces in a conductive–convective heat transfer system were studied [115]. The enhanced cooling of a gas-turbine blade trailing edge with curved air flow in the pin-finned wedge system was suggested and tested [116]. A counter-current two-phase flow model for boiling heat transfer on T-shaped finned surfaces was proposed [117].

Heat transfer enhancement in a two-phase closed thermosyphon was reported that, under the experimental conditions, the boiling heat transfer coefficient increased by 1–3 times and the condensation heat transfer coefficient will be 67–100% higher as compared with that of a usual thermosyphon [118]. Boiling heat transfer in gravity heat pipes were discussed [119].

Experimental results with R11 and R113 showed that the condensation heat transfer coefficient for a saw-tooth-shape finned tube will be ten times as large as that of a smooth tube [120]. The method for augmentation of an in-tube condensation heat transfer for stratified flow with an inserted coil was advanced, and was tested with R11 [121].

HEAT EXCHANGER

A mathematical model was deduced to describe regenerator performance in consideration of the effect of longitudinal heat conduction of a solid matrix, temperature dependence of thermal properties of fluid and the effect of the reversals, a numerical solution was obtained over a wide range of applications, and the influence of various factors were discussed [122, 123].

The thermal performance of crossflow heat exchangers with a non-uniform inlet fluid temperature was investigated with both analytical and numerical methods, a generalized effectiveness expression of heat exchangers was proposed for the better understanding of the heat transfer process in crossflow heat exchangers [124]. An improved mathematical model and the mean temperature difference characteristics of crossflow heat exchangers with one fluid mixed and the other unmixed was reported in refs. [125, 126]. A criterion for heat exchanger performance was evaluated and discussed in refs. [127, 128]. The assessment of the channel geometry on heat transfer performance and flow resistance in a plate heat exchanger were presented in ref. [129].

A mathematical model, 'discrete flow model', used for calculating the temperature of fluid when it flows from the exit of a heat exchanger, was established [130]. Analysis on heat transfer processes in 1–2 and 1–3 split flow heat exchangers and new charts for logarithmic mean temperature difference correction factors were reported in ref. [131]. A method of selecting the heat transfer surface for gas–gas heat exchangers was presented in ref. [132].

It was proposed that a heat-pipe heat exchanger can be treated as a conventional shell-and-tube heat exchanger so far as the arrangement of tube bundles and calculation methods are considered, some design problems were summarized [133].

INDUSTRIAL HEAT TRANSFER

Heat flux meters may be used extensively in China to indicate and control the heat loss through the shell of heat equipment or from heat piping. The heat transfer analysis was made on a high-speed calibration device suggested for heat flux meters [134]. The possible disturbance of the temperature field due to the heat flux meter and its error for heat flux measured were analysed [135]. The transition time for the surface-installed heat flux meters was also estimated analytically [136].

Heat transfer problems with high values of Gr, consequent low Re/Gr, that occur in the cement industry, were investigated experimentally, and the conditions for which the effect of natural convection can be neglected were found [137]. A method for enhancing the cooling of a horizontal rotating cylinder using air jet blow was proposed [138].

The artificial freezing procedure of stream and the temperature distribution of the freezing-wall were analysed by the finite element method, a simple and effective method was presented for calculating transient heat conduction with release of latent heat [139].

The climatological methods for estimating ultraviolet global radiation and diffusive radiation under various sky conditions were suggested according to a series of radiation measurements at ten cities in different regions [140].

The heating and evaporation processes of a single coal–water slurry droplet under forced convection were studied, and a calculation model was established [141]. The temperature and velocity field of flowing slurry at various tube sections were obtained in terms of a numerical approach of its momentum and energy equations, and the drag and heat transfer coefficients of COM (coal–oil mixture) flowing in a tube with constant wall temperature were determined both analytically and experimentally [142]. A packet model was derived for heat transfer between the fluidized bed and the immersed tube surface, with the consideration of the presence of surface resistance and its effect on local voidage by introducing a physically justified property boundary layer [143]. As to prevent sulfuric acid corrosion at high temperature, a model on the temperature field of the front part of a boiler and a corresponding method for calculation with emphasis on treating the non-linear and conjugate boundary conditions were proposed [144]. Heat transfer in the radiation chamber of a cylindrical tubular heater for processing crude oil was analysed [145].

A numerical method suggested for calculating the temperature rise of the friction brake will provide a favourable condition for designing a mechanical press [146]. The heat transfer behaviour of the solidification process of a $Hg_{1-x}Cd_xTe$ alloy which is an ideal material widely used for infra-red detectors, in a cylindrical quartz ampoule was presented and the temperature fields in the ingot of alloy and in the wall of the quartz ampoule were analysed and calculated [147].

A set of empirical correlations covering a wide range of spacing, obtained by using the transient technique for natural-convection heat transfer across air layers inclined at various angles, were given. Based on these correlations, it was shown that there are two ranges of the optimum air layer spacing with small convection heat loss from the view of variation of convection heat loss with air layer spacing [148]. Using the net radiation method, a rational model for simulating the thermal process of a direct gain passive solar house was worked out [149].

MEASUREMENT TECHNIQUE

The infra-red multi-spectral radiative pyrometry, which is based on the principle of the multicolour technique and on the principle of equalization of two spectral radiances, was investigated, and it was shown that this method can diminish the effect of emissivity on the accuracy of measurement [150]. The surface temperature of a liquid droplet was measured with an infra-red technique in ref. [151]. The thermal stability of a laser cavity was discussed in ref. [152].

The temperature field pictures and hot boundary layers around the fins in forced liquid flow were taken successfully by using the laser real-time interference method [153].

A scheme of the double film heat flux gauge was presented in ref. [154], which can measure simultaneously the heat flux at low and high frequencies.

The measuring techniques for simultaneous measurement of thermal conductivity and diffusivity of moist porous materials by a transient hot-wire method were discussed in detail, so as to assure the reliability of measuring results [155]. A transient technique for simultaneously measuring the thermal conductivity and diffusivity of viscous liquids was also reported [156].

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Abbreviations: *JETP—(Chinese) J. Engng Thermophys.*; *JCIE—(Chinese) J. Chem. Ind. Engng*; *JSE—Acta Energiae Solaris Sinica* (*J. Solar Energy*).

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