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My 50-year life in studying heat transfer

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ABSTRACT

In this paper my personal experiences in the study of heat transfer in the past 50 years were summarized by 26 subjects. Each one was briefly qualitatively described with some related publications. To some extent this paper reflects one aspect of the development history of heat transfer study in Xi'an Jiaotong University of China in the past half century.

1. Introduction

I was admitted to Jiaotong University of China in the Fall of 1957, the second year since the university moved from Shanghai to Xi'an and graduated from Xi'an Jiaotong University (XJTU) in the Summer of 1962 from the Department of Power Machinery Manufacturing Engineering. I was lucky enough to be admitted as a graduate student under the supervision of Professor S. M. Yang to study heat transfer (HT) who received his Ph D in 1953 under the supervision of Professor M. Jakob at Illinois Institute of Technology in Chicago of USA. I received my diploma of graduate study at the end of 1966 and joined the teacher staff of XJTU. From October 1980 to December 1982, I had the honor to work with Professor E. M. Sparrow as a visiting scholar in the Heat Transfer Laboratory of the University of Minnesota of USA. I returned China at right beginning of 1983 and since then have been working in XJTU. As a professor and researcher in HT and fluid flow (FF) I have been working in this discipline for more than 50 years. My major research fields are numerical heat transfer and enhancement of convective heat transfer. The research experiences of mine since 1983 are briefly summed up as follows.

2. Research experiences of twenty-six subjects

2.1. Sign preservation principle

The scheme used for the discretization of convective term is an important issue in the finite volume method (FVM). Stability is one of the main challenges. For a stable scheme no matter how large the grid step and velocity are the numerical solution is stable, while conditionally stable scheme may lead to oscillating numerical solution. Up to 1987 several methods for analyzing stability of a scheme had been proposed. However, no one can be applied to analyze all the existing schemes. Based on physical consideration we proposed the sign preservation principle. The basic idea is as follows: the studied scheme is used to discretize the convection term of 1-D transient diffusion-convection equation, and diffusion term is discretized by central difference (CD). From physical consideration, it is required that the induced values at the two neighboring points at next time level, denoted by $\phi_{i\pm1}^{n+1}$, by an original disturbance at point i and time level n, denoted by ε_i^n, should satisfy following condition:

$$\frac{\phi_{i\pm1}^{n+1}}{\varepsilon_i^n} \geqslant 0 \tag{1}$$

That is the sign of $\phi_{i\pm1}^{n+1}$ should be the same as the original disturbance [1]. And the condition that makes the above inequality valid can determine the critical Peclet number of the scheme beyond which numerical solution of the scheme will be oscillating. This is a very simple and physically meaningful requirement. The stability of all the existing schemes can be adequately analyzed by this principle, and no exception has been found.

2.2. From SCSD to a general way of construction of new schemes

At the end of last century and beginning of this century we paid much attention on the scheme construction, and proposed SCSD [2] and SGSD [3], the latter of which unconditionally stable with second order accuracy and less effect of false diffusion. In the development of schemes a question was raised: all the existing schemes for convection term were proposed individually. Is there a unified way to construct schemes in the framework of FVM. This question was successfully solved in [4,5], where a general way for construction of schemes in FVM was proposed, and all the existing schemes can be derived from the proposed method.

Another issue in the scheme construction at that time is that whether a scheme could have both absolute stability and high accuracy. The dominant view at that time was that the two characteristics of a scheme

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are in contradiction, and lower order scheme could be absolute stable, while higher order scheme can only be conditionally stable. It turns out not the case.

In [4,5] it has been shown that once the coefficient of the interpolation of a scheme can satisfy some condition, one scheme can be both absolutely stable with order of accuracy more than 2.

2.3. Improved criterion for convective boundedness

Boundedness is another issue in the scheme construction. If numerical solutions do not overshoot or undershoot the values inherently governed by the physical process, then the adopted convective scheme is called possessing convective boundedness. The well-known criterion was Gaskell-Lau criterion for convective boundedness condition (CBC) [6]. This CBC was claimed both sufficient and necessary. The study in [7] first pointed out that this CBC is not necessary, and a new bounded scheme was proposed which does not satisfy the condition required by G-L CBC. Later in [8] example showed that a scheme satisfying G-L CBC may lead to physically unreasonable solution, and an improved criterion was proposed. It is interesting to note that some new scheme proposed by other authors without being aware of this improved CBC automatically fulfill this improved CBC. And all existing boundedness-preserving schemes satisfy this improved CBC.

2.4. CLEAR-IDEAL algorithms for coupling velocity and pressure

For numerical solution of incompressible fluid flow the SIMPLE algorithm has been widely adopted. It is semi-implicit in that when the correction of a velocity is determined the effects of its neighboring points are totally neglected. This semi-implicit feature affects both convergence rate and robustness, and many variants were proposed since the SIMPLE algorithm was proposed in 1972. However, all these SIMPLE-family algorithms can not completely overcome the semi-implicit feature. The key is that in SIMPLE-family algorithms velocity is up-dated by adding a small correction into the intermediate one. The CLEAR algorithm was proposed in [9,10] in which the updated velocity is re-solved by the momentum equation rather than by adding a small correction. The convergence rate and robustness are greatly improved. Later in [11,12] based on the CLEAR algorithm the IDEAL algorithm was invented in which multiple double inner iterations (one for pressure and the other for velocity) are executed. The convergence rate and robustness are significantly further enhanced.

2.5. Outlet boundary condition treatment when there is recirculating flow

For numerically solving N-S equations in an open system, disputes existed on how to locate the outlet boundary. One important opinion is that the outlet boundary should be positioned at a place where there is no recirculating flow, otherwise the numerical solution would be meaningless. This method not only takes a larger computational space but also sometimes is hard to implement. Stimulated by a practical engineering problem, cooling process of a TV-screen after it was taken out from a furnace, we proposed a practical method [13] to deal with such kind situation: the outlet boundary can be positioned at any place required, and for the velocity component normal to the outlet boundary it is determined by local mass conservation, while for the component parallel to the outlet boundary it is determined by zero 1st order derivative normal to the boundary. Then the local normal velocities at the outlet are modified by the condition of total mass conservation over the solution domain. We compared the results of different numerical treatments with our test results and found that the results of the proposed method agree with the test data satisfactorily, while for others there are qualitative differences between numerical results and test data.

2.6. Numerical techniques for an isolated island in fluid

In the simulation of 2D flow field and heat transfer, it is often encountered that an isolated island is located in the field without any connection with the boundaries. The conjugated method is an efficient way in which both fluid region and solid region are solved simultaneously with sold region being regarded as a special fluid of very high viscosity. How to deal with such island by this conjugated method puzzled our team for several years. Finally numerical details were figured out as follows [14,15]: (1) Setting zero initial values for u^0 , v^0 in the island at each iteration; (2) Setting zero values for u^* , v^* in the island by setting very large coefficients of the main diagonal element of momentum equations; (3) Setting near zero values for u' , v' by setting a very small value for the coefficient d; (4) Transferring near zero velocity in the island to its boundary—at each iteration setting the diffusion coefficient very large and adopting harmonic mean for interface interpolation.

2.7. Additional source term method and its applications

First kind boundary condition is the most favorable condition for numerical simulation. For the 2nd and 3rd kinds of boundary condition the so-called additional source term methods (ASTM) may be used in which the energy transferred at the boundary is regarded as the internal source of the 1st control volume adjacent to the boundary. After adding this additional source term, the connection of the boundary adjacent control volume to the boundary may be completely cut and when solve the algebraic equation this boundary may be regarded as 1st kind. This is very efficient numerical treatment and can save appreciable computational time. In [16] the ASTM was introduced, and a derivation process was provided for its rationality. In addition, this method was adopted in a number of practical problems. In [17] the ASTM was used to deal with the surface radiation between different surfaces of the refrigeration chamber. In [18] the slotted fin efficiency was numerically determined by adopting ASTM, and in [19] the natural convection in conjugated single and double enclosures was solved by applying this numerical method.

2.8. Study on some grid-generation techniques

To overcome the most severe disadvantage of FVM, the study on grid generation methods for irregular domain attracted great research interests in the 1980s to 1990s. Our team's work includes followings. First in the 2nd edition of the textbook [16] a whole chapter was arranged to give detailed presentation on the methods of body-fitted coordinates (BFC). It turns out that among many textbooks of numerical simulation for HT and FF, the contents of BFC given in [16] is the most detailed. An automatic grid generation method for 2D Delaunay triangle was introduced in [20]. The multi-surface method was adopted in [21] to generate the grids of twisted square ducts with uniform, divergent and convergent cross sections. A method for generating anisotropic triangles was proposed in [22], where the stretches in different directions are very different. By the proposed methods the aspect ratio of the generated triangle may be as large as 2000. And such kind of grid is very useful for turbulent boundary layer flow computation.

2.9. VOSET-an efficient phase interface capturing method

The basic feature of boiling heat transfer is the generation, growing and departing of vapor bubbles from surface. Interface capturing method is one of the methods for simulating bubble behavior. Among several interface capture methods, Volume of Fluid (VOF) and Level Set are probably the most widely used ones. VOF and Level Set have their own advantages and disadvantages and have compensated each other: VOF can guarantee mass conservation but cannot get an accurate interface curvature, while Level Set is just the opposite. Thus, developing a combined one becomes an inevitable trend. But such combination should not be simply putting two methods together. We figured out an efficient combination method VOSET [23]: let VOF to determine the bubble mass and Level Set to calculate interface curvature; in addition, the curvature is determined by a geometric method, rather than by solving a differential equation. Thus, the efficiency and accuracy of the interface capture are greatly improved. In [24] VOSET was successfully extended to 3D case. It now finds wide applications in solving engineering problems.

2.10. Nucleate boiling and film condensation simulations with LBM

One disadvantage of the interface capture method for simulating boiling heat transfer is that a vapor nucleus must be set in priori as its starting point. Only meso-scale and micro-scale numerical methods may simulate the generation process of a gas bubble from liquid state. Our team conducted some investigations in this regard by LBM. A 3D multi-relaxation-time (MRT) phase change lattice Boltzmann method in conjunction with conjugated heat transfer treatment was proposed in [25] and applied to simulate the nucleation on roughened surface without introducing any artificial disturbance. It is found that the surface cavity shape has significant effect on the nucleation process. The ratio of liquid density over gas density in [25] is 17. In [26] by using a smaller value of a coefficient in the P-R equation of state, the density ratio of liquid over gas was extended to 200. Of course, this ratio is still quite lower than practical value. For example, water at atmosphere has this ratio about 1600. A large room is left for further improvement. In addition, film condensation HT with non-condensable gas was also investigated by LBM in [27].

2.11. Two categories of multiscale simulation

When times goes into 21 century, multiscale simulation becomes a hotspot in the international numerical simulation community. However, when we carefully examined the cases for which multiscale simulation are needed, we found that different researchers have different understanding on what they mean multiscale problems. From the view of numerical simulation, we found that it is necessary to classify two categories of the multiscale problems: multiscale process and multiscale system [28,29]. For the multiscale process:different regions have different governing equations and numerical methods. Numerical solutions should be coupled at the interfaces. For the multiscale system: the same governing equations and the same numerical method are used at different regions. The difference is the size of grid step. The two typical examples are the transport process in a proton exchange membrane fuel cell (PEMFC) and the heat transfer in a data center, respectively. To the authors' knowledge, so far, all multiscale heat transfer problem studied in literatures can be divided into these two categories.

2.12. Coupling methods between FVM/LBM/DSMC/MDS

Then for the multiscale process the coupling of solution at the interfaces of different regions where different numerical methods are used becomes an important issue. Methods of nanoscale, microscale /meso-scale and macroscale are adopted for different regions, and solutions are exchanged at the interfaces to obtain the entire full solution. Numerical solutions (information) exchange at the interfaces of the neighboring regions can be mathematically expressed by two operators:

$$\Phi = C\phi \quad \phi = R\Phi \tag{2}$$

where Φ and ϕ are macroscopic parameters (say velocity) and meso-scopic or microscopic parameters (say distribution function in LBM), respectively, and C and R are compression and reconstruction operators, respectively. The operator C is easy to be defined, say by different average method, but the operator R is difficult to be constructed, because it is here that less information (say velocity at a point in FVM) from one solution region should be converted to much more information (say the density distribution functions in LBM) for a neighboring region. For the coupling of solutions from FVM and solutions from LBM, successful reconstruction operators were proposed by our team in [30–32]. In the multiscale atomistic-continuum methods periodic boundary condition is no longer applicable because of inhomogeneity of the atomistic region.To move away from the periodicity condition at the boundary of MD simulated region while still keeping correct mean pressure on the MD system, a boundary force should be applied on atoms near the boundary. An equation for determining such force is proposed in [33]. And the coupling between FVM and DSMC was studied in [34].

2.13. Thermal conductivity determination of braided composites

Braided composites made from braided fabrics as reinforcing phase in an appropriate matrix are widely used in aerospace engineering, automobile industries and other related fields because of their low weight and high strength. In the widely used materials with reinforcing fiber, such as the braided composites, carbon fiber exhibits relatively serious anisotropy between axial and transverse thermal conductivities, and the determination of their effective thermal conductivity provides a big challenge. The heat conduction characteristics of 3D four-directional braided composite were studied at both *meso*-scale (for braiding yarns) and macro-scale (for composites) with appropriate boundary conditions in [35]. Different shapes of braiding yarns' cross- section are considered. And the model is validated by experimental results. In [36] numerical prediction of the effective thermal conductivities of plain-woven composites was performed. Three reducing-size unit cells were formulated by using different symmetries exhibited in the composite, including translational, reflectional and rotational symmetries, and corresponding thermal boundary conditions were derived and validated.

2.14. The effect of inter-cylinders on convective heat transfer

Let us now make some summary on our study of enhancing heat transfer. Heat transfer enhancement is an ever-lasting subject in the HT study. Professor S M Yang gave us the course of HT in Spring of 1959, and he emphasized of the course beginning that HT enhancement is one major task of HT study. Plate fin-and-tube HT surface are widely used to enhance gas side HT. From the geometric point of view, the major characteristics of the plate fin-and-tube heat transfer surface, as compared with plain duct, are the existence of the interwall tube cylinder. Even though a number of studies have been performed for different kinds of plate fin-and-tube HT surfaces, no one claimed the effects of the interwall cylinder on HT. This study was conducted in [37] by naphthalene sublimation method. It was found that the interwall cylinder serves as a turbulence promoter. It may significantly enhance HT in the low Reynolds number region. And the existence of the interwall cylinder also causes the earlier transition from laminar to turbulent flow.

2.15. Our contributions to the development of field synergy principle (FSP)

Even though enhancing HT has been studied for more than one century, up to the end of the last century it was still not clear on what is the basic mechanism of enhancing convective HT. Guo proposed the field synergy principle (FSP) for HT based on laminar incompressible boundary layer over a plate (parabolic flow) [38] which says improving the synergy between velocity and fluid temperature gradient is the basic mechanism (indicated by the angle between the two vectors). Later FSP was extended to elliptic flow [39], compressible hyperbolic flow [40] and turbulent HT [41]. In addition, it is also shown that the FSP can unify the existing mechanisms of enhancing single phase convective HT

[42]. For complicated enhancing technique such as the vortex generator it is also revealed that improving synergy between velocity and temperature gradient is the basic mechanism [43]. We also revealed by numerical examples that the evaluation results for a number of enhancing techniques by the FSP and the entransy theory is fully consistent [44]. The FSP is adopted to guide the development of new enhancing techniques such as the Front Sparse-Real Dense slotted fin surface [45,46].

2.16. Gas and water heat transfer enhancement in tube

When air and water are the two HT medium, usually air is set outside the tube where a large room can be used to develop fin surfaces. However, because of some demand of structure sometimes cooling water may be set outside the tube transversely flowing the tubes and hot air goes in the tube. To enhance air-side HT longitudinal fins may be adopted. In order to fix the fin usually a small tube is set in tube coaxially and fin surfaces are set between the annular space of the two tubes. Such kind of heat exchanger is used as gas cooler in some compressors. In the experimental measurement of the tube HT and friction factor we conducted two variants: one with the inner tube blocked, i.e. no air flows through it, and the other with the inner tube not blocked. To our surprise, within a certain range of ratio of the outer tube diameter over the inner tube diameter, the HT rate of the center-blocked one is appreciably larger than the one not blocked at the same flow rate, and this is what we call center-blocked tube with internally finned longitudinal wave-like fins [47]. Later we analyzed the HT and FF numerically and found that the superior HT performance of the center blocked tube is because an appreciable improvement in synergy caused by the increased velocity gradient at the outside tube. In addition, based on the test data of our own and of literature for water flowing in tube with microfins we extended the Gnielinski equation to determine the turbulent average HT coefficient [48].

2.17. Heat transfer and fluid flow in mini-micro tubes

Historically, severe diversities and deviations once existed between the measurement results for friction factor and Nusselt numbers of microchannels by different authors. With the progresses in fabrication method, measurement and data acquisition techniques, the reasons for such deviations and diversities are gradually revealed. And it is now generally accepted that, except those size effects (rarefaction and compressibility effects of gases, and the effect of surface roughness, etc.), conventional solutions and correlations for fluid flow and heat transfer of single-phase flow can still predict the fluid flow and heat transfer behavior in microchannel. Our team is one of such research units in the world made such a statement [49,50]. In revealing the size effect, we found that when the surface relative roughness is less than 1%, gas fluid flow in microchannel abide by conventional theory. However, for microchannel with diameters less than 10–20 μm, there exists rarefaction effect [51]. The effects of two-dimensional wall and fluid axial heat conduction for a conjugate heat transfer problem in simultaneously developing laminar flow and heat transfer in straight thick wall tubes with constant outside wall temperature were numerically investigated in [52]. It turns out that the basic function of the wall axial heat conduction is to unify the inner wall surface heat flux. In [53] FF and HT in a wavy channel with a hydraulic diameter of 500 microns were numerically studied. And the three-dimensional parabolic turbulent forced convective HT and FF in multi-curved channel with a gap of 1.5 mm were numerically simulated in [54]. The major results of our team for gas microchannel fluid flow and heat transfer are summarized in [55].

2.18. Phase change heat transfer of refrigerant alternatives

To replace the ozone-depleting working substances worldwide researches were widely conducted in 1990 s. Our team mainly worked on alternatives of 152a and 134a and published the first paper of experimental results on 152a condensation outside single sooth and finned tubes in 1994 [56]. It was revealed that at a saturation temperature of 40 °C, the condensation HT coefficient of 152a is about 20–25% higher than that 0f R-12. Then the test facility of in-tube convective forced condensation and boiling was built up and experimental measurement and theoretical analysis were performed for the alternative 134a. In [57,58] experimental investigation on local heat transfer characteristics of 134a forced convection inside smooth horizontal tubes for condensation and boiling HT were, respectively, reported. Later, experimental results of boiling heat transfer in smooth and micro-fin tubes of four refrigerants (including R134a and R410a) were presented in [59].

2.19. Heat transfer of falling film evaporation outside tubes

Falling film evaporator is known as a potential substitute to pool boiling evaporator in a water chiller or heat pump system due to its intrinsic advantages over pool boiling like less refrigerant charge, smaller size, smaller temperature difference of heat transfer and easier oil removal, etc. Many studies have been performed, however, there are still lack of satisfied heat transfer correlations, and even there isn't a well-accepted heat transfer correlation of horizontal single smooth tube of refrigerants. Based on our previous experimental studies [60–62], the HT correlations of refrigerant falling film evaporation on a single horizontal smooth tube was proposed in [63]. Two correlations for five refrigerants were constructed. The correlation for full wetting regime fits 96.7% of total 542 our own data within ± 30% deviation while fits 73.4% of total 289 data of other authors from −30% to + 15%; the correlation for partial dryout regime fits 97.5% of our own data within ± 30% while fits 76.8% of total 95 data of other authors within ± 30%.

2.20. Study on the triboelectric nanogenerator

From 2016 to 2017 under the auspices of the university, our key laboratory built a microfluidics laboratory. Based on this laboratory several microfluidics studies were conducted, and triboelectric nanogenerator (TENG) is one of them. It is a revolutionary energy harvesting technology that converts the mechanical energy into electricity by utilizing triboelectricity. A large variety of the TENGs have been developed with different structural designs, for the applicability and flexibility for various energy sources and various applications. Our team also conducted some investigations in this regard [64]. We proposed a new structure in which the electrode and hydrophobic layer were used as the top plate and the electrode was used as the bottom plate. Our experimental results show that this structure outperforms other devices, which is also supported by our theoretical analysis on the influence of the dielectric layer on the output power. In addition, the dependence of the optimal load resistance on the droplet number and the vibration frequency was experimentally studied.

2.21. Three-element approach for determination of thermal contact resistance

Thermal contact resistance (TCR) is a key factor on the thermal protection system design in the aerospace engineering. During the past decades, numerous studies have been conducted to determine the TCR between various materials. One dimensional steady state method is the most widely used one to measure TCR based on the Fourier's law of heat conduction. To determine the TCR of a pair of material the interface temperature difference should be measured, in addition the thermal conductivity of the test material should be given. To present the measured results of TCR one major parameter, the averaged surface roughness should be provided. Thus, the measurement of interface temperature difference, test specimen thermal conductivity and the surface roughness of the test specimen consist the three elements of TCR determination. This idea was actually presented in [65], where numerical simulation method for TCR by using ABAQUS was also presented. For the studied material pairs of Ti-6Al-4V—Ti-6Al-4V in [65], the simulated results are compared with the experimental data, and the maximum deviation is 9.57% while 75% deviations of the results are within 5%.

2.22. Comprehensive evaluation of techniques for HT enhancement

Heat transfer enhancement technique provides a powerful tool to improve the thermal performance of heat exchanger. However, any HT enhancement technique will induce a bigger pressure drop, and it is a common knowledge that the ratio of pressure drop increase is often larger than the ratio of heat transfer enhancement. Thus, the question of how to comprehensively evaluate the enhancement technique is brought to attention. A number of evaluation criteria were proposed. With the emerging of worldwide crises of energy shortage, the energy-saving purpose of heat transfer enhancement has become more crucial. A comprehensive evaluation approach based on the comparison between enhanced and referenced HT surfaces for identical flow rate, identical pressure drop, and identical pumping power was proposed in [66], and a performance evaluation plot was proposed. In this plot the ratio of the friction factor of the enhanced surface over that of the referenced surface and the ratio of the related heat transfer enhancement at the same Reynolds number are taken as the abscissa and ordinate, respectively. The 1st quadrant surrounded by the two coordinates can be divided into four regions: in region 1 HT enhancement is obtained with larger pressure drop penalty such that per identical pumping power the HT is deteriorated; in region 2 HT is enhanced per identical pumping power but deteriorated per identical pressured drop, in region 3 HT is enhanced per identical pressure drop, and in region 4 the HT enhancement ratio is larger than the friction factor increase ratio under identical flow rate. In this plot different enhanced techniques for the same referenced one can be easily and clearly compared for their energy-saving performance.

2.23. Energy utilization efficiency of different section of engineering

For the purpose of energy conservation and greenhouse gas emission reduction, Chinese government has made great efforts on taking measures of energy saving. One of the measures is to decide whether a newly planned factory should be approved or an already existed factory should be shut down according to their energy efficiency (EE). A Hierarchical Indicator Comparison (HIC) method by Energy Efficiency Indicator (EEI) System to evaluate energy efficiency (EE) for different industry sectors in China is presented in [67]. The basic idea of the HIC method is to compare EE of a plant with reference values based on indicators. If comparison results show that this plant is worse than the reference, this plant will not be permitted to be established. A chemical industry named purified terephthalic acid (PTA) is chosen as an example to illustrate the HIC method. In addition, a hybrid forecast method for forecasting and evaluation on regional energy efficiency of China was proposed in [68]. Based on these studies a comprehensive review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry was made in [69].

2.24. Solar-assisted air cleaning system with hybrid solar chimney and photovoltaic system

Solar-assisted air cleaning system is a new attempt to control air pollution by using solar energy. A demonstration unit was built in Xi 'an in 2016, which is the world's first building structure to use solar energy and advanced filtration technology for air purification [70]. This unit has a chimney of 60 m height and a collector of 2580 m^2 area. Our team was partially involved in the design, test and evaluation of this demonstration unit. The solar energy is used to generate thermal updraft air to attract the polluted air from the environment, polluted air is purified by the filters set up before the air inlet of the chimney, and then is vented to the environment through the chimney. The important output parameter of such a facility is the air flow rate through the chimney. Basically, the larger the collector area the more the air flow rate. The larger air flow rate is obtained at the cost of land. Numerical studies are performed to investigate a hybrid system consisting of a solar chimney and photovoltaic (PV) panels covering the collector and a system consisting of a solar chimney only. Results show that the hybrid system with 40-meter-wide PV panels covering the entire top of the collector will reduce the system volumetric flow rate only by 19% while increase the system total electric power output by 57 times [71]. The generated electricity can be used to rotating a fan for driving more air through the chimney. Thus, the solar-assisted air cleaning system covering all collector surface by PV panels is an efficient variant to save the land.

2.25. Re-independence study for environmental turbulent boundary layer flow

For the study of pollution transport in city street we may adopt both numerical simulation and wind tunnel test. To conduct the wind tunnel test a question arises: how to determine Reynolds number? When airflows past streets, the so-called atmospheric boundary layer (ABL) is formed. Similarity theory requires that to make the process in wind tunnel similar with the prototype, two conditions must be satisfied: (1) geometric similarity; and (2) flow dynamic similarity, i.e., the Re of wind tunnel test must equal to Re of the prototype. If a model with 1/500 of the prototype is used, the average velocity is 4 m/s. Then the velocity in wind tunnel should be 2000 m/s! This is not manageable in an ABL wind tunnel. We built a numerical wind tunnel, which is fully similar to the physical wind tunnel, and adopted three two-equation turbulence models in the simulation [72]. Numerical results showed that the environmental turbulent boundary layer flow can be divided into two regions: strong Re-dependent at low Reynolds number range and weak Re-dependent at higher Reynolds number. A concept of ratio of relative change was proposed to determine the critical Reynolds number which distinguishes the two regions. If the Reynolds number in the prototype is in the weak Re-dependent region, then its wind tunnel test can be conducted at any Re larger than the critical one which is usually much less than the prototype Reynolds number. Thus, identifying the critical Reynolds number will provide great convenience for wind tunnel test.

2.26. Application of similarity theory in the study of PEMFC

Our team started investigation of water-thermal management of Proton Exchange Membrane Fuel Cell (PEMFC) since 2000. The most important integrated performance of PEMFC is its polarization curve (PC) affected by dozens of dimensional parameters. To numerically predict this PC we developed several models and the corresponding codes [73–76]. Since it is affected by several dozens of parameters, up to now the polarization curves are obtained dimensionally for individual group of such parameter values, and each curve can only be applied for this specific group of parameters. A comprehensive review of the applications of the similarity theory in the study of various components of PEMFC is conducted in [77] and similarity analysis is adopted for a three-dimensional single-phase isothermal model of PEMFC to derive similarity criteria in [78]. Seven kinds of input criteria are obtained, and dimensionless voltage and dimensionless current density are defined as two output criteria. Numerical verifications show that if the seven criteria keep their individual values with their components vary in a wide range, the dimensionless polarization curves keep the same with a deviation about 1%, showing the validity and feasibility of the present analysis. From the effect on the dimensionless polarization curve, sensibility analysis shows that the seven criteria can be divided into three categories: strong, mild to minor, and negligible. The similarity analysis approach can greatly save computation time in modeling the output characteristics of PEMFC.

3. Short conclusion and acknowledgments

From the above brief presentation it can be seen that heat transfer is a very active sub-fields in the thermo-fluid science. Great changes are happening in HT study at the moment with the world development of science and technology. As the Chinese proverb says one is never too old to learn, I will keep track of its development and do whatever research I can.

I was so lucky that I had the honor to learn HT under the supervision of Professor S. M. Yang and Professor E. M. Sparrow; I am very lucky that I have been working with more than 160 lovely and hard-working graduate students; I am very fortunate that I can teach and research HT conscientiously and harmoniously with many young and helpful colleagues in our team; in addition, the development of our team has long been supported from many colleagues' home and abroad. I would like to take this opportunity to express my sincere thanks to my advisors, my students and my colleagues' home and abroad.

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Because of presentation limitation some subjects that I had conducted were not listed above. I appreciate the understanding of those students who executed the subjects.

Last but not the least I would like to show my sincere thanks to my wife Yu-Qin Sun for her constant support in the past half century.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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