对流换热及其强化的理论与实验研究最新进展

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不连续介质中传热传质的建模、数值模拟及实验研究课题总结

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陶文铨　何雅玲　等编著

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杨世铭教授简介

1925 年 1 月 5 日生于江苏无锡。1942—1944 年就读于交通大学。1944 年任教于无锡职校。1945 年任正泰橡胶厂工程师。1946—1948 年继续就读于交通大学，并于 1948 年获学士学位。同年赴美国法莱尔伯明翰工厂实习。1949 年入美国凯思理工大学学习，1950 年获硕士学位。同年入美国伊利诺理工大学学习，1953 年获博士学位。1953 年底回国，继续任职于正泰橡胶厂。1956—1959 年任教于交通大学。1959—1985 年任教于西安交通大学，历任副教授、教授。1981 年任我国首批博士生指导教师。1985—1994 年任教于上海交通大学，1994 年年底退休。

主要的社会兼职有：曾任中国工程热物理学会理事、常务理事，1999 年起任荣誉理事；《工程热物理学报》杂志编委(1980—1999 年)；国家教委热工课程教学指导委员会副主任(1980—1999 年)；《国际传热传质学》杂志荣誉编委(1982—2003 年)及国际传热传质学中心理事(1987—1998 年)。

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前　言

5年前，西安交通大学、华中科技大学、东南大学工程热物理专业的部分教师有幸承担了国家973基础研究项目“高效节能的关键科学问题”第三课题《不连续介质中传热传质的建模、数值模拟及实验研究》课题(G2000026303)。在华贲教授、过增元院士两位首席科学家的领导下，经过全体课题组成员5年的不懈努力，现在已经全面完成了研究任务。为了做好课题的总结工作，我们决定出版一本专集，对所进行的研究专题进行全面的总结，归纳所取得的成绩，探讨今后的研究方向，同时收录主要的发表论文，以便于作者与读者的今后查阅。

2005年又正好是我国传热学研究与教学的奠基人之一杨世铭教授80华诞。本课题组的成员，从年过六旬的资深教授到20余岁的有为青年，几乎都是读着杨世铭先生的名著《传热学》而成长起来的。杨世铭先生一生从事传热学的教学与科研，涉及的领域很广，主要的研究方向是对流换热基本规律的探索与强化，这正是本专集的内容。因此我们也将本专集作为献给杨世铭教授80华诞的一份薄礼。

杨世铭先生虽然已经退休，但他仍然关心国内外传热学的研究与发展。特别是还继续在流体自然对流换热的流态从层流到湍流的判断准则方面进行着开创性的工作，提出了应该以Grashof数而不是以Rayleigh数作为判断指标的观点，而后者在国内外传热界已经沿用了近半个世纪。近年来的国内外实验研究的结果，正在不断地给先生的论断提供新的证据。我们特地将先生有关这一工作的近作收入本文集并作为开篇，以表示我们对先生的敬业精神和敢于向传统观点挑战精神的敬重。

根据课题的研究任务，本课题组的主要研究教授分别从6个方面写出了研究总结，作为本文集的第一部分。本文集的其他部分分别按照专题收录了这5年中本课题组发表的而且标注有973项目资助字样的部分论文，共计国际杂志37篇，国内期刊10篇，国际会议3篇。这些论文都已经在正式出版的刊物或论文集上发表，为尊重原刊物，文献的著录格式均维持原样。限于篇幅不可能收录所有的论文，因此在文集末尾收录了所有论文的名称。同时还收录了杨世铭教授退休前所指导的两位研究生的有关论文。特别值得指出，本论文集收录的论文最晚的出版日期是2005年1月，实际上此后还有不少研究成果发表，因出版周期的需要，未能收入在内。在书末的成果总结表中也有同样的遗憾。例如华中科技大学刘伟教授所负责的项目“新型卫星热控技术”已经于2005年4月22日通过由总装备部预研管理中心组织的鉴定，鉴定组专家认为“合同研究内容全部完成、技术指标全部实现、关键技术全部突破”。但因时间关系，未能收录在统计表内。

本论文集编辑过程中西安交通大学能源与动力工程学院热流中心的研究生吴志根，李茹，杨卫卫，闻春华，陶于兵，谢旭良，王勇，李卓，高亚甫，石磊，张剑飞，樊菊芳，王小佳等在文稿清理、文件转换、检索查证等方面给予了不少帮助；高等教育出版社编辑宋晓，陈大力，李心桂三位同志给予了积极的支持，没有他们的帮助，很难设想短期内本书能够付印出版，特在此一并致谢。

西安交通大学能源与动力工程学院

陶文铨

何雅玲

2005年5月　识于西安

目　录

专题总结论文

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Progress on researches for physical laws of natural convection heat transfer in past decade

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ABSTRACTS

A previous review on this subject appeared in 1994. This is a second review covering the period of past decade. Significant contributions on this subject appeared in this period. The adoption of *Gr* number as the transition criteria and extension and improvement of experimental data lead to the creation of new formulations of the physical laws on free convection heat transfer. In the literature, visualization of flow in boundary layer as well as additional experimental results appeared in this period. In this review, the essential features of the new formulation will be presented and the relevant progress in literature will be discussed.

KEY WORDS: Natural convection, Heat transfer, Physical laws

1. THE NEW PHYSICAL LAWS PROPOSED

Summarizing all recent achievements, a new formulation of the physical laws of natural convection heat transfer was proposed by the author in 2001[1]. The basic form of the correlation can be expressed by the following form.

$$Nu = C\,(GrPr)^{n}\,\phi \tag{1}$$

where ϕ denotes the physical property correction factor. C, n and the application range for different configurations can be determined by experiments. For the most important cases of vertical plate and horizontal cylinder, recommended values of C, n and recommended values of the range of application in terms of the *Gr* number are shown in Table 1. The experimental basis of these recommendations are given by the author[2].

Table 1. Recommended *C* and *n* values in Eq. (1)

Geometry	*Gr* range	*C*	*n*
Horizontal Cylinder	$1.43\times10^{4}\sim5.76\times10^{8}$	0.48	1/4
	$5.76\times10^{8}\sim4.65\times10^{9}$	0.0165	0.42
	$>4.65\times10^{9}$	0.11	1/3
Vertical plate	$1.43\times10^{4}\sim3\times10^{9}$	0.59	1/4
	$3\times10^{9}\sim2\times10^{10}$	0.0292	0.39
	$>2\times10^{10}$	0.11	1/3

The features of the new formulation may be summarized as follows:

1. The *Gr* (Grashof number) is adopted as the transition criterion instead of the *Ra* (Rayleigh number). The *Gr* number plays the same role in the natural convection that the *Re* (Raynolds number) number plays in forced convection as can be derived from the momentum equation by similarity analysis theoretically.

2. A physical property correction factor ϕ is incorporated in the basic equation. For air, $\phi = 1$ under usual conditions. Any forms of ϕ may be used to cases where they have been proven to be effective. Tentatively a correction fac-

tor $(Pr_f / Pr_w)^{0.11}$ has been recommended to be used in different conditions, but more work remains to be done in order to remove its tentative status.

3. In between the laminar and turbulent regimes, a transitional regime was identified. The n value in the correlating equation of the transition regime is higher than the n value of the correlating equation of the turbulent regime. The recognition of the transition regime not only helps to locate the transition criteria more precisely but also to reflect the physical status of the flow. The introduction of the transitional regime is a substantial improvement of our understanding of the physical phenomena.

4. For the turbulent regime, independent experimental results for different bodies, such as the vertical plate and the horizontal cylinder, identical correlating equations are obtained. This result confirms that in the turbulent regime correlation, the length scales cancel out and the heat transfer is independent on characteristic length.

2. DISCUSSION OF SELECTED TOPICS

(1) Is there any experimental support for the turbulent correlation for natural convection heat transfer of horizontal cylinder by Churchill and Chu[3]? This question must be answered because this turbulent correlation is entirely different from the correlation of the new formulation.

Three sets of data appear on the correlation plot in the original paper of Churchill and Chu. The first set of data is the data of Ackermann[4]. As has been pointed out by the author[5], only part of these data belong to the natural convection category, and the rest of the data with the effect of boiling should be excluded from the natural convection category. As shown in Fig. 1, the data in the natural convection category fall on the laminar natural convection correlation of the new formulation nicely. The data on Churchill and Chu plot are the data with the effect of boiling. The second set of data is the mass transfer data of Schutz[5]. They convert the mass transfer coefficient directly to the heat transfer coefficient in a way without experimental verification. The Schmidt numbers of Schutz experiment ranges from 1 714 ~ 2 073. The heat transfer data are air and water data with Pr number ranges of 0.7 ~ 6. It is doubtful that without experimental verification any conversion of mass transfer coefficient to heat transfer coefficient with wildly different Sc and Pr numbers will preserve the experimental status. The third set of data is the data of Kutadeladze[6]. These data are numerical results of a hypothetical fluid with a Prandtl number of 1.0. To sum up, in the turbulent correlation of Churchill and Chu, no acceptable experimental data has been found.

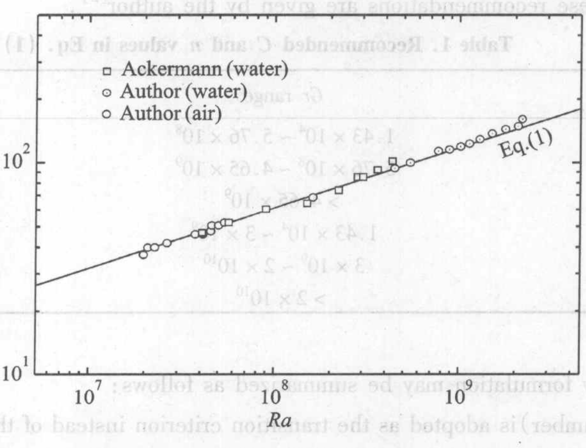

Fig. 1. Plot of data in the natural convection category.

(2) Are the recent experimental results of Clemes et al.[7] correct? This is a good question. This question had been raised by Morgan[8] at the end of conclusion section in his recent survey. Different from other steady state experi-

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mental methods, a transient experimental method has been employed by Clemes et al. The results they obtained are somewhat lower than other steady state experimental results, but are closer to the numerical results. It must be pointed out that in actual experiments, some local disturbances not predicted by numerical method have been revealed. As has been shown by Eckert and Soehnghen[9] waves occur in the laminar boundary layer in the region well before the transition. The occurrence of sharp rise of local Nu number near the trailing edge of the heated cylinder has been reported recently by Kitamura et al.[10] The inability to count for these phenomena excludes the numerical method as the standard to compare with. The author incline to take the existing best experimental results as the standard to compare with new experimental results. The consistent lower values of Clemes results in the range of $10^4 \sim 10^7$ indicate the weakness of his experimental method.

(3) Discussion on the minimum containment diameter ratio D_c/D is the next topic. In the experimental research of natural convection for horizontal cylinder, a minimum containment diameter ratio should be observed in order to get accurate results free from the influence of circulation of flow caused by the ceiling of the container. The effect of the containment diameter for air has been studied by a number of workers. Wide differences exist for different workers. The author is in favor to adopt the recommendation by Hessani et al. that $D_c/D = 10$ for 2.6% error[11]. For water, however, no recommendations were available at the time when the author worked on this subject. For the purpose to obtain a recommendation for water, an experimental study had been taken with different D_c/D: 1.5 and 3.45. The experimental set up and instrumentation are the same as in [12]. The results show that the data for $D_c/D = 3.45$ agree very well with the laminar correlation line, while the data for $D_c/D = 1.5$ are higher than the laminar correlation. The data points for D_c/D are shown on Fig.2. On these grounds, $D_c/D = 3.45$ is tentatively recommended by the author as the minimum containment diameter ratio for water. A recent work of this subject appeared in 2003. Atmane et al. stated that preliminary experiments showed that above $D_c/D = 3.5$ heat transfer around the cylinder and the natural convection hydrodynamics were not affected by the water surface[13]. Their value is in substantial agreement with the tentatively recommended value of the author. The tentatively recommended value had been used to examine the recent water data of Kitamura et al.[13] Only a limited part of their water data meet the criterion $D_c/D > 3.45$. Specifically, these data are for $D = 60$ mm, 114 mm and 165 mm. However, equation (1) was not properly expressed in [13]. The physical property correction factor is missing. A revised correct plot is shown in Fig.3. All acceptable water data of Kitamura et al. are shown in this figure. As can be seen from Fig.3, these water data are in general agreement with the equation of the author.

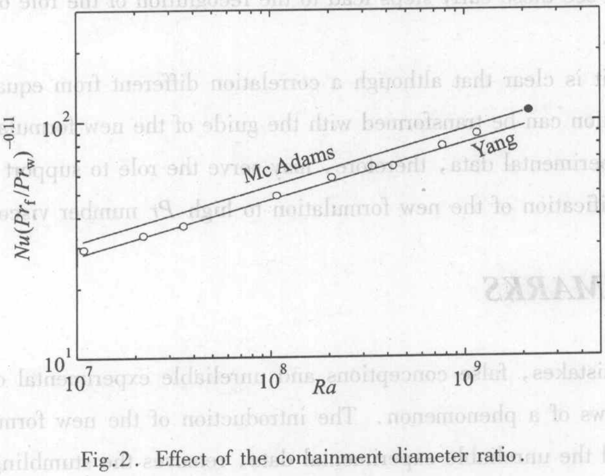

Fig.2. Effect of the containment diameter ratio.

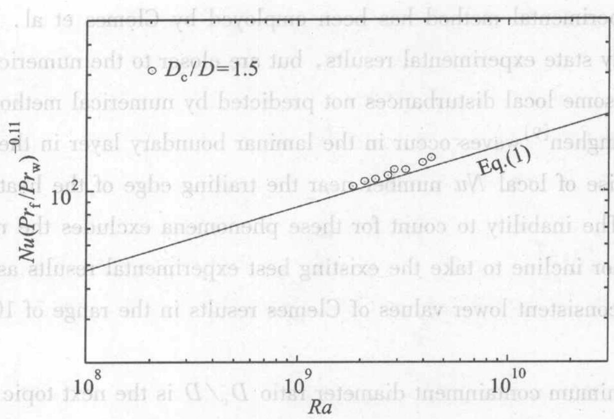

Fig.3. Recent water data in literature compared with Eq. (1).

3. EXTENSION OF COVERAGE OF THE NEW FORMULATION

Up to now, the coverage of the new formulation is rather limited. For the geometry of vertical plate and horizontal cylinder, coverage of Pr number range also should be extended. Tremendous works remain to be done. Efforts in these respects are cordially welcome. In the spirit of promoting these efforts, a revisit by the author on the work of Touloukian et al. [14] will be reported below. Extensive experimental data for natural convection heat transfer on a vertical cylinder to ethylene glycol and water were obtained. As stated in that paper Pr number of the ethylene glycol may be taken as 40. If we take the alternative form of ϕ as suggested by Fand et al. [15] $\phi = Pr^{0.047}$, the laminar correlation of Touloukian et al. may be expressed in the following form with an error less than 3%:

$$Nu = 0.726\ (GrPr)^{1/4} = 0.59\ (GrPr)^{1/4}\ Pr^{0.047} \tag{2}$$

The transition criterion of the laminar flow of the new formulation $Gr = 3 \times 10^9$ agrees also with their data. Significant departure of the laminar line occurs above Ra of 1.2×10^{10}. This indicates the beginning of the transition region. Touloukian et al. found that they were not able to correlate their data of ethylene glycol and water by a single line. Separated correlation for different fluids form parallel correlating lines on the figures in their paper. The parallel correlating lines for different fluids indicate that there is a missing parameter closely connected with the Pr number in the correlation of different fluids. In the new formulation, this missing parameter is identified as the physical property correction factor. It is rewarding to see these early steps lead to the recognition of the role of this physical property correction factor in early publications.

From the above analysis, it is clear that although a correlation different from equation (1) was recommended by Touloukian et al., their correlation can be transformed with the guide of the new formulation into the form almost identical to equation (1). Their experimental data, therefore, may serve the role to support the new formulation. The task of extension of experimental verification of the new formulation to high Pr number viscous fluids is partly realized.

4. CONCLUDING REMARKS

It is not uncommon that mistakes, false conceptions and unreliable experimental data retard the progress of our understanding of the physical laws of a phenomenon. The introduction of the new formulation rejects the adoption of Ra as the transition criteria and the unreliable experimental data, removes the stumbling blocks in the development of the physical laws of natural convection heat transfer. This new formulation incorporates significant advances in our understanding of the physical laws of natural convection heat transfer and is expected to supersede the previous formulation in a not too distant future.

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强化迁移过程的基本理论——场协同原理及其应用

陶文铨，何雅玲，屈治国，李增耀　曾　敏

（西安交通大学）

摘　　要

在执行973项目“高效节能的关键科学问题”第三课题《不连续介质中的传热传质的建模、数值模拟及实验研究》过程中，本课题组对由过增元教授提出的场协同原理进行了多方面的深入研究，获得了一系列的进展。本文试图对本课题组在过去5年中有关场协同原理方面的研究成果做一总结。

关键词：强化换热，场协同，迁移过程，数值模拟，实验研究

1. 引　　言

在我们生活的世界中发生着各种各样的过程，可谓大千世界，包罗万象。其中与人类的生存关系最密切的物理过程之一是热量的传递：从现代楼宇的暖通空调到自然界的风霜雨雪的形成，从航天飞机重返大气层时壳体的热防护到微机械系统中的有效冷却，从一年四季人们穿着的变化到人类器官的冷冻储存，无不都与热量的传递过程密切相关。传热学就是研究由温差引起的热能传递规律的科学。凡是有温差存在的地方，就有热量(传递过程中的热能)自发地从高温物体向低温物体传递。自然界和各种生产技术领域中到处存在着温差，因此热量的传递就成为自然界和生产技术领域中一种极普遍的物理现象。因而传热学的基本原理虽然已经形成了近一个世纪，但直至今日仍然是热科学乃至整个技术科学中十分活跃的学科。从传热学发展的历史来看，20世纪60年代以前，研究的重点是揭示基本传递现象的规律。在20世纪60年代及以前出版的文献与教材中，几乎没有出现“强化传热”（heat transfer augmentation，enhancement）的术语。发生于20世纪70年代的能源危机对世界的经济发展和科学研究是一次大冲击，迫使人们尽力减少石油与其他二次能源的消耗。这在客观上极大地促进了强化传热技术的研究——其实质是探求在消耗一定能量的条件下尽可能多地传递为某种过程所需的热量。根据Bergles的统计[1]，这个时期及以后世界范围内关于强化传热研究论文的数量急剧上升，如图1所示。所以自20世纪70年代以来强化传热成为国内外传热学界研究的热门课题。进入20世纪90年代以后，强化传热的技术开始由第2代向第3代发展[2~5]，并且取得了突出的成绩，最近又提出了第4代强化传热技术的概念[6]。

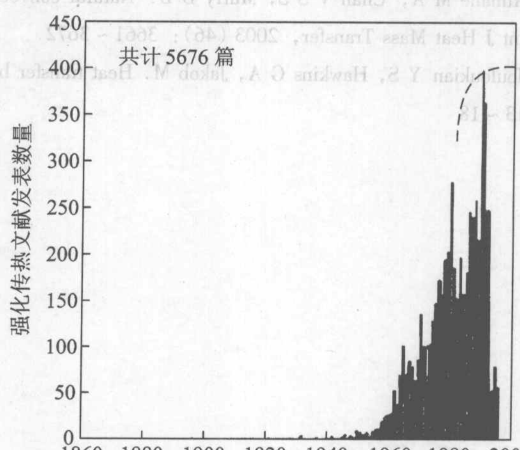


图1　强化传热文献发表数量的逐年增长情况

但是强化传热研究开展近半个世纪以来，关于强化传热的实质究竟是什么，即使对于最简单的单相强制对流换热，直到20世纪末，也没有一个统一的解释。文献中现有的一些说法都可以解释部分强化换热的技术，但不能解释全部强化传热技术。1998年我国学者过增元教授对边界层型的流动进行了能量方程

的分析，通过将该方程在热边界层内的积分，证明了减小速度矢量与温度梯度之间的夹角是强化对流换热的有效措施[7~9]，以后这一基本思想被称之为“场协同”原理(field synergy principle)。文献[11]中对强化传热的场协同原理的内容作了以下全面的表述：速度与温度梯度之间的协同越好，在其他相同的条件下换热就越强烈；速度场与温度梯度两个矢量场的协同就意味着：① 速度与温度梯度间的夹角应尽可能地小，两者应尽量平行；② 速度，温度梯度以及夹角余弦的局部值应该同时比较大，也即，夹角余弦大的地方，速度与温度梯度之值也应该比较大；③ 对于内部流动，截面上的速度分布与温度分臣应尽可能地平坦(饱满)。局部协同性好的地方局部 Nusselt 数就比较大。

本课题组在过去近 5 年执行国家基础研究项目的过程中对这一原理进行了深入、广泛的研究，获得了一系列有价值的结果。以下本文从 7 个方面，分别对本组的研究工作成绩做一总结。

2. 场协同原理从抛物型流动推广到椭圆型流动

在工程技术中遇到的对流传热过程大部分属于椭圆型流动，因此非常有必要将文献[7,8]中对抛物型流动作出的分析推广到椭圆型流动，并查明成立的条件。文献[12]完成了这一证明工作，简述如下。

对如图 2 所示的流体流过后台阶的换热，在稳态情况下能量方程为

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \quad (1)$$

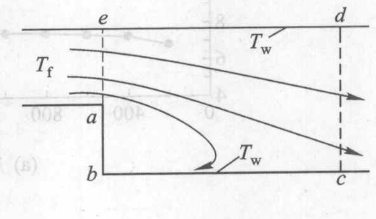


图 2　流过后台阶的换热

将式(1)对图中所示的区域 $abcdea$ 做积分，得等号前面与流动有关的部分(记为 FM)及等号后与导热有关的部分(记为 HD)分别为

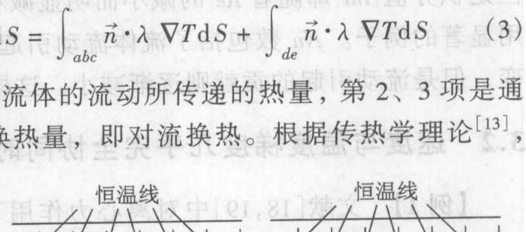
$$FM=\iint_{\Omega=abcdea}\rho c_p(\vec{U}\cdot\nabla T)\mathrm{d}x\mathrm{d}y \quad (2a)$$

$$HD=\iint_{\Omega=abcdea}\left[\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)\right]\mathrm{d}x\mathrm{d}y \quad (2b)$$

对 HD 应用高斯积分降维定律，并将通过 cd，ea 部分的导热移到等号前面，最后得

$$\iint_{\Omega=abcdea}\rho c_p(\vec{U}\cdot\nabla T)\mathrm{d}x\mathrm{d}y-\int_{cd}\vec{n}\cdot\lambda\nabla T\mathrm{d}S-\int_{ea}\vec{n}\cdot\lambda\nabla T\mathrm{d}S=\int_{abc}\vec{n}\cdot\lambda\nabla T\mathrm{d}S+\int_{de}\vec{n}\cdot\lambda\nabla T\mathrm{d}S \quad (3)$$

式中 $\vec{n}$ 是计算区域边界的外法线。式(3)等号前第 1 项是通过流体的流动所传递的热量，第 2、3 项是通过流体的导热所传递的热量，等号后是固体表面与流体间的换热量，即对流换热。根据传热学理论[13]，当流动的 Peclet 数大于 100 时，流体中的导热相对于流体运动所传递的热量可以略去不计。对于绝大多数工程领域中的对流换热，流动的 Peclet 都大于 100，因而减小 $\vec{U}$ 与 ∇T 间的夹角是强化对流换热的根本措施。即使对 Peclet 数小于 100 的情形，式(2a)部分仍然在对流换热中占相当大的比重，因此减小 $\vec{U}$ 与 ∇T 间的夹角仍然是强化对流换热的有效措施。



(a) 流体被加热　(b) 流体被冷却

图 3　速度与温度梯度协同的理想情况

我们在文献[14]中对速度与温度完全协同的理想情况进行了分析(图 3)，指出当速度与温度梯度完全协同时，就可能使换热量与流量的一次方成正比，即 Nusselt 数与 Reynolds 数的一次方成正比。

3. 场协同原理的数值与实验验证

在科学技术的发展过程中常常有这样的现象：一个新的概念刚提出的时候，或者由于它有悖于常规

的认识，或者它表面上看来普通，以前不被人们关注，从而需要大量的论证例子来加深人们对新概念的认识。场协同原理的发展多少也经历了这样的过程。这里将基本上沿着历史发展的进程简述各个方面的验证例子。

3.1 高 *Pe* 数下对流项的整场积分代表换热量的数值验证

由式(2a)可见，当流动的 Peclet 数较高时，该式实际上代表了对流换热量，对于场协同原理的验证首先就是从这一步入手的[15~17]。目前这一点已经成为共识，这里不再细述。我们只指出一点，就是这样的数值例子本身又给上面分析中关于流动 Peclet 数影响的论述提供了佐证。以两平行板通道内的层流换热/二维顺排板束的层流换热为例，计算得到的对流项积分 *Int* 以及平均 *Nu*（Nusselt）数随 *Re*（Reynolds）的变化给出在图 4 中。

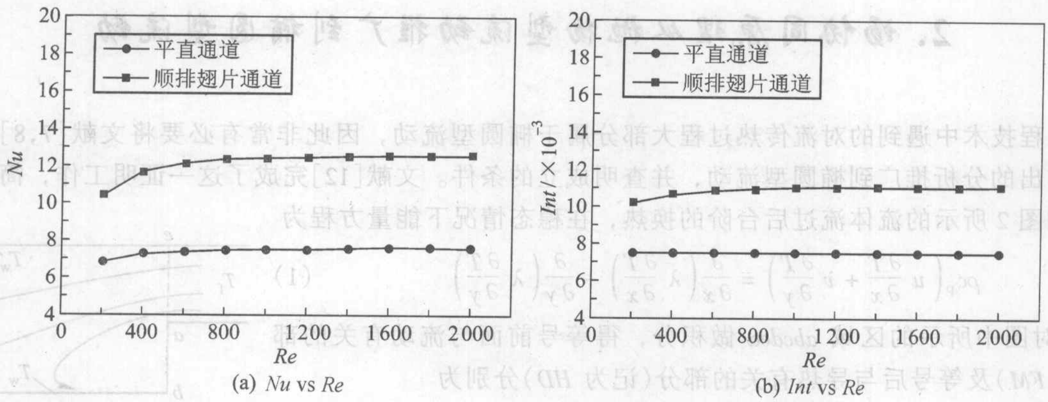


图 4　对流项积分与 *Nu* 随 *Re* 的变化

图中不仅显示了 *Int* 与 *Nu* 随 *Re* 的变化趋势完全一致(板束的 *Nu* 以及 *Int* 值高于平行通道，在 *Re* 高时，*Nu* 与 *Int* 与 *Re* 数无关)，而且还可看出，随着 *Re* 的减小，平直通道的 *Nu* 并不变化(理论值为7.54)，但是积分值 *Int* 却随着 *Re* 的减小而明显减小：这就是当 Peclet 数(*RePr*)小于 100 时流体中的轴向导热作用显著的例子。*Nu* 数包括了流体流动引起的能量转移与轴向导热的贡献在内，因此 *Pe* 小时，其值不变，但是流动引起的贡献则逐渐减小。这样例子在一般的传热学文献中并不多见。

3.2 速度与温度梯度几乎完全协同时 *Nu* 正比于 *Re* 的实验与理论验证

【例 1】 文献[18,19]中对离心力作用下的对流换热进行了理论分析及实验验证。离心流化床是通过旋转床体使物料受到离心力场作用的一类新型流化床，在干燥、燃烧、除尘和核反应等领域有重要的应用前景。理论分析表明，在离心力场的作用下，所形成的多孔物料层内对流换热过程中，在一定的转速范围内，速度与温度梯度(热流矢量)平行，气流通过多孔物料层时的强制对流换热的 *Nu* 数与 *Pe*（= *RePr*)成线性关系。实验结果表明，在离心流化床中离心力场对于对流换热的强化存在一个最佳的转速范围或者最佳的流化状态范围，在该范围内 *Nu* 数与 *Pe* 成线性关系。

离心流化床中气固两相换热系数的实验准则关系式为

$$Nu_{\mathrm{p}} = 0.002\,42 Pe\left(\frac{L_0}{d_{\mathrm{p}}}\right)^{-0.647}\left(\frac{r_0\overline{\omega}^2}{g}\right)^{-0.152} \tag{4}$$

对于不同大小的离心力场，满足 *Nu* - *Pe* 为直线关系的 *Pe* 数范围有所不同。把满足 *Nu* - *RePr* 为直线关系的 *RePr* 数的最大值称为临界 *Pe* 数。从 96 组离心流化床中气固两相强制对流换热实验值得到的临界 *Pe* 数如下：在床体转速为 400 r/min 时 *Pe* = 100，而在床体转速为 600 r/min 时，*Pe* = 200。在床体转速为 300 ~ 650 r/min 范围内，*Pe* = 810 (图 5)。

当 *Pe* 数大于临界 *Pe* 数以后，离心流化床中的对流换热强度会明显减小，换热系数随流速增长

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