热线概念及场协同原理的比较及其对传热学理论发展的贡献

A Comprehensive Review and Comparison on Heatline and Field Synergy

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目 录

Bejan: IJHMTransfer 2015, 81:654-658, 在题为 "Heatlines (1983) versus synergy (1998)"[1] 写道:

Both concepts, heatlines and synergy, are about visualizing the physics of convection, which is the combination (superposition) of heat conduction lines and enthalpy flow lines over a material in motion. Heatlines and synergy are reviewed here comparatively. This comparison reveals that synergy is a remake of heatlines, and that synergy has no physical connection with heat transfer enhancement.

1. 是否heatline 与synergy 都是为了对流换热的可视化?

2. 是否 synergy (FSP)在物理方面与强化传热无关?

3. 是否 synergy 是 heatline的改头换面?

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Heatlines (1983) versus synergy (1998)

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ABSTRACT

A picture is worth a thousand words. This article is about a picture known as "heatlines" since 1983, and "synergy" since 1998. Both concepts, heatlines and synergy, are about visualizing the physics of convection, which is the combination (superposition) of heat conduction lines and enthalpy flow lines over a material in motion. Heatlines and synergy are reviewed here comparatively. This comparison reveals that synergy is a remake of heatlines, and that synergy has no physical connection with heat transfer enhancement. At bottom, it has become a lot easier to take an existing idea change some key words and drawings and publish the old idea as new.

Bejan教授的文章

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1983 年 Kimura/Bejan 在ASME JHT 发表一篇Technical Note: The "Heatline" Visualization of Convective Heat Transfer.

模仿二维不可压缩流动的速度与流函数的关系：

$$u = \partial \psi / \partial y;\ v = -\partial \psi / \partial x \quad \xrightarrow{\text{自动满足}} \quad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

从二维稳态无源项的对流扩散方程（能量方程）：

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

提取出两个方向的对流扩散总通量

$$J_x = \rho u c_P T - k\frac{\partial T}{\partial x};\quad J_y = \rho v c_P T - k\frac{\partial T}{\partial y} \quad \longrightarrow \quad \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} = 0$$

定义一个**H**函数为：

$$J_x=\frac{\partial H}{\partial y}=\rho u c_P T-k\frac{\partial T}{\partial x};\qquad J_y=-\frac{\partial H}{\partial x}=\rho v c_P T-k\frac{\partial T}{\partial y}$$

$$\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=\frac{\partial^2 H}{\partial x\partial y}-\frac{\partial^2 H}{\partial y\partial x}=0$$

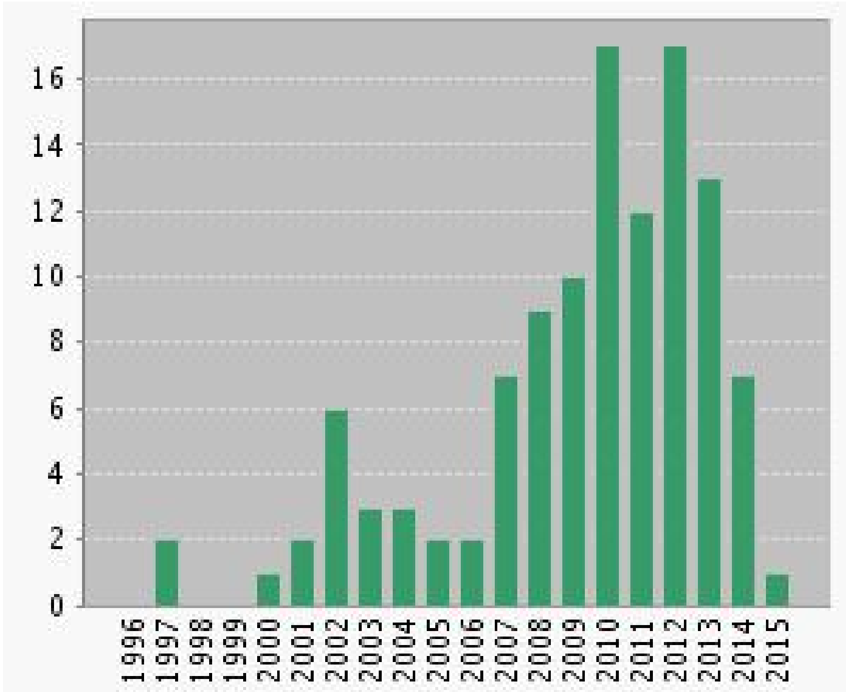
H 为常数的线是二维问题中对流与扩散传递的能量为定值的线，显示了热能的传递路径， 称为热线（**Heatline);** 为了获得热线需要求解一个关于**H**函数的泊桑方程

$$\boxed{\frac{\partial^2 H}{\partial x^2}+\frac{\partial^2 H}{\partial y^2}=\rho c_P[\frac{\partial}{\partial y}(uT)-\frac{\partial}{\partial x}(vT)]}$$

1987年**Trevisa/Bejan** 又将此概念推广到质交换，提出了**Massline**的概念**[2]**。

目　录

3.1 热线概念提出后学界的发展



热线（**Heatline)**提出后的**20**余年中每年发表了不少论文

为了做出公正的对比与综述我们查阅了百余篇期刊发表的有关热线及其应用的文章。

热线（Heatline)自1983年提出后，学界的反应比较热烈，而且有以下发展：

1）推广到二维圆柱坐标系 [3,4 for r-z][5,6 for r-theta];

推广到极坐标 [7]

2）推广到非稳态对流换热 [8,9]

3）推广到湍流 [10]

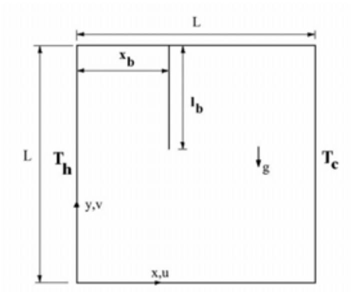
4）推广到多孔介质问题 [11]

5）推广到各向异性材料 [12]

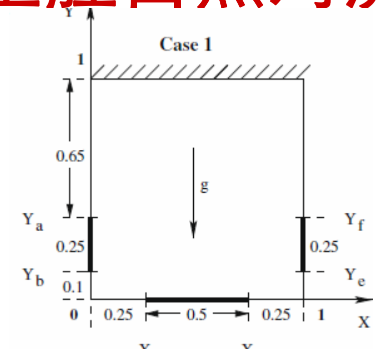
6）推广到反应流 [13,14]

3.2 热线概念提出后学界的应用

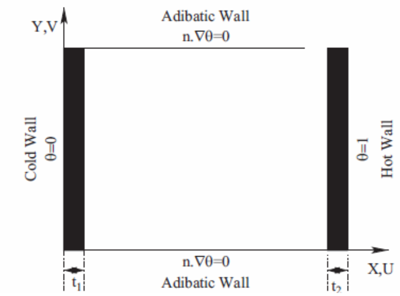
3.2.1 二维空腔自然对流问题热传递路径的可视化



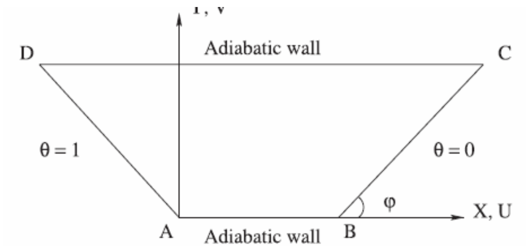
带分隔板
(20, 46)



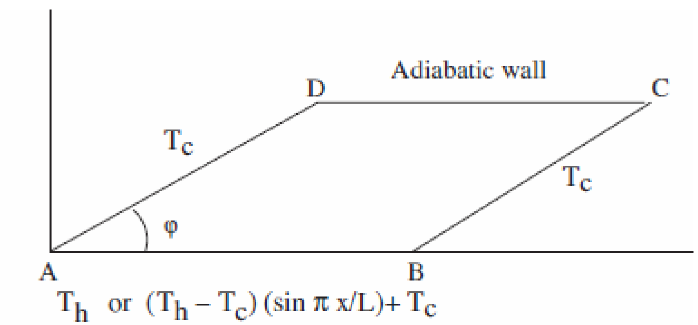
离散热源（17,39,51, 57,77,78,80,107)



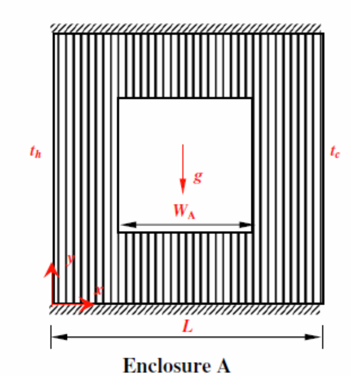
耦合传热(15)

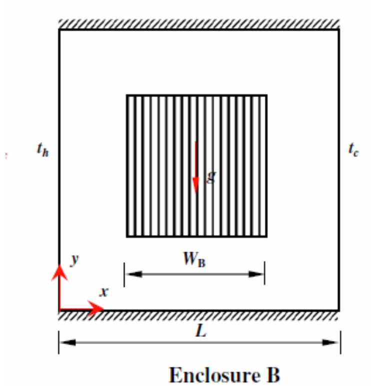


梯形空腔
(4,14,40,53,72)

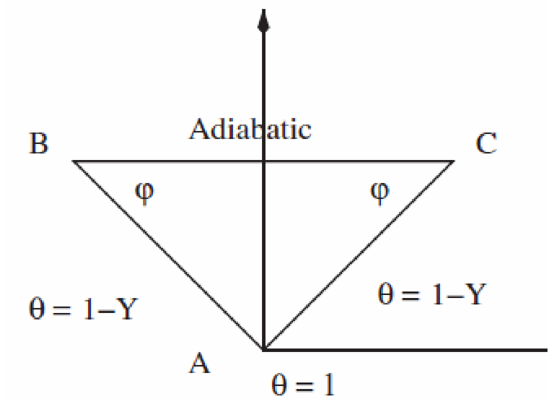


菱形空腔自然对流(12,31,32)

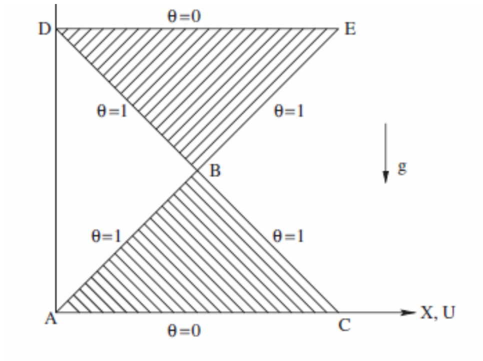




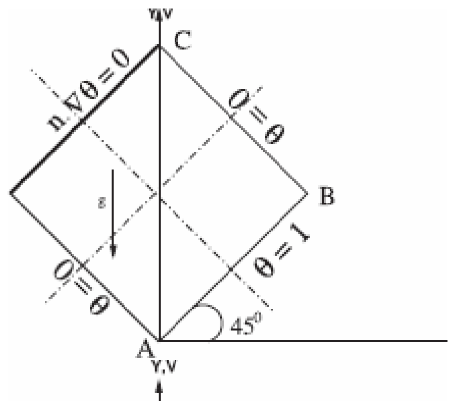
耦合问题可视化
(90,92,108,113)



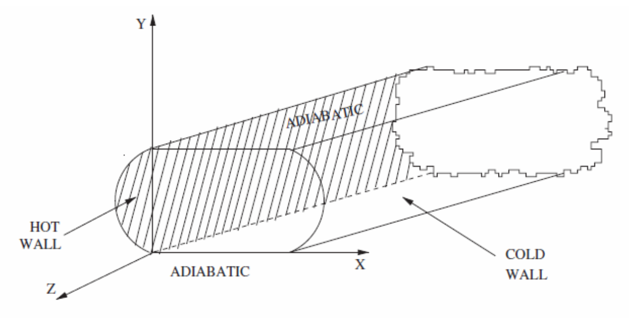
等边三角形空腔
（16,73）

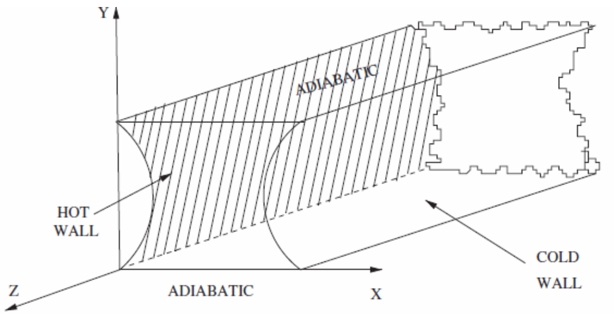


倒置双三角形
（54,55， 60， 74）

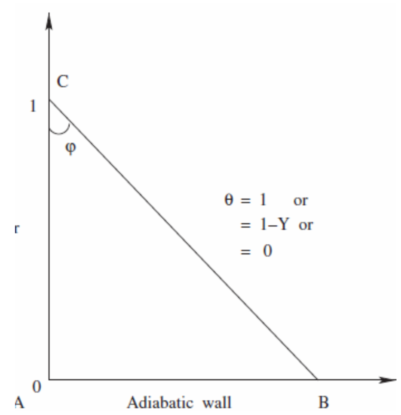


斜置方腔自然对流
（3,14,30,37)

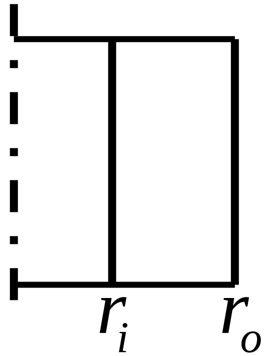




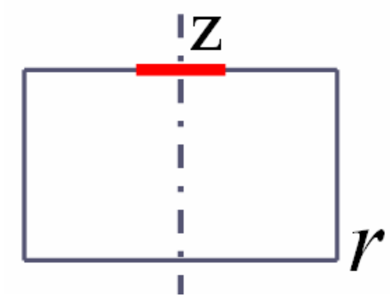
凹凸面空腔自然对流(7)



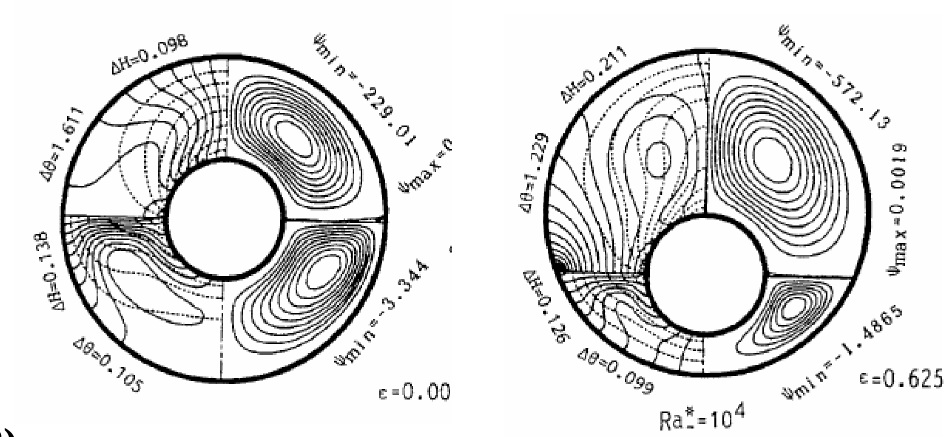
直角三角形（56）



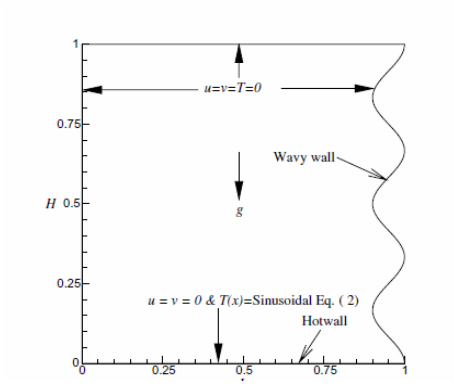
竖直环形空腔自然(119)



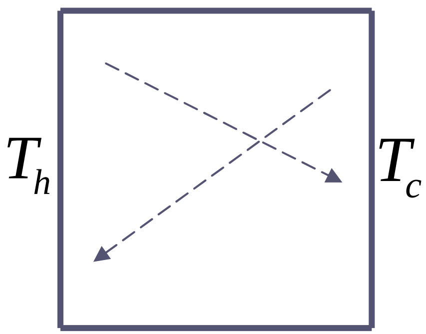
圆柱形空腔自然(118)



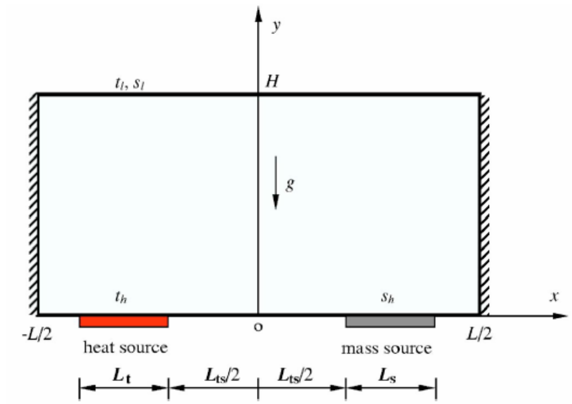
环形空腔自然 [3]



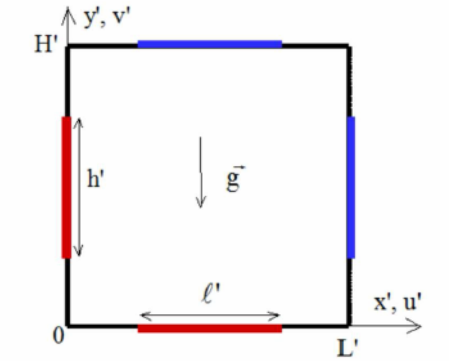
复杂表面 (86)



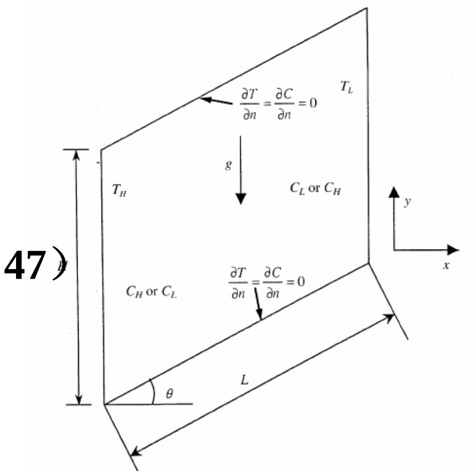
辐射性气体
空腔对流（117）



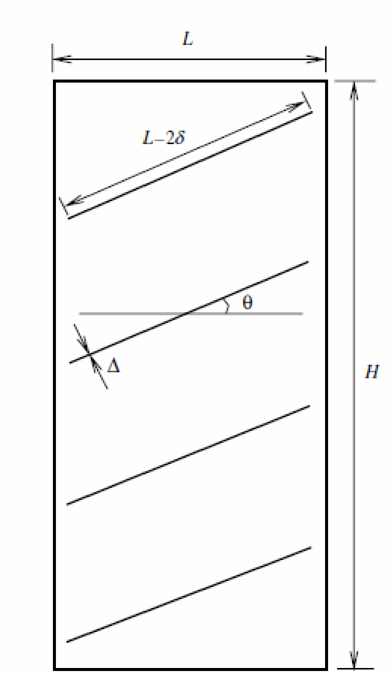
热质对流（88）

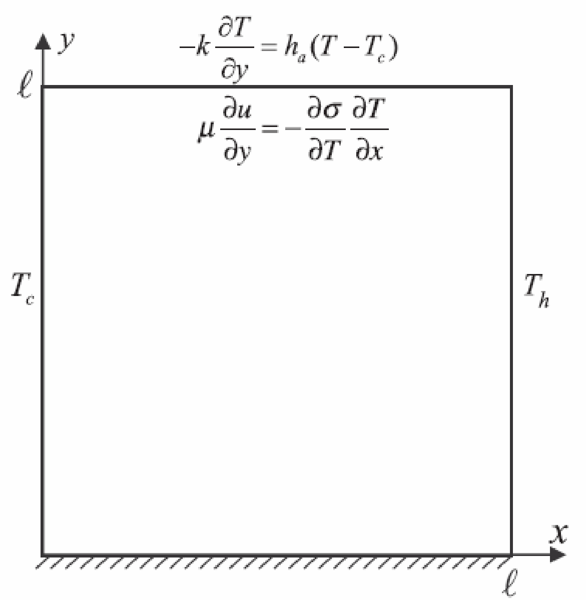


离散加热壁面有辐射（36,42，47）

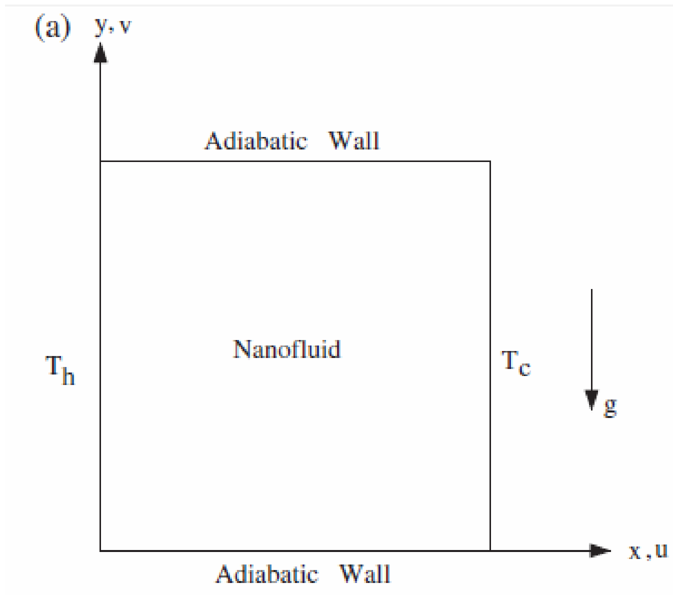


平行四边形空腔制热双扩散（100）





表面张力对空腔自然对流的影响（25）



纳米流体空腔自然对流（23）

多层分隔板（97）

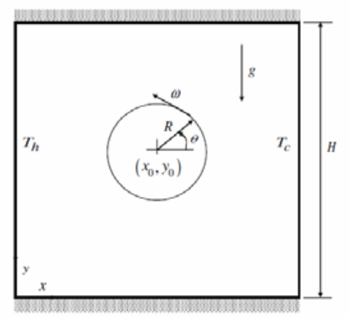
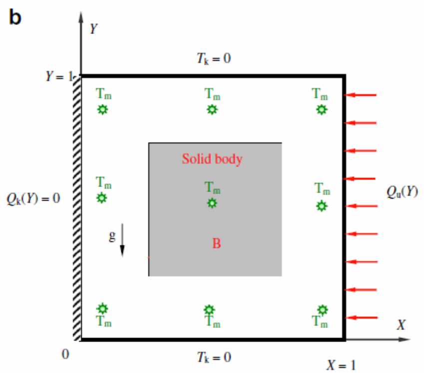
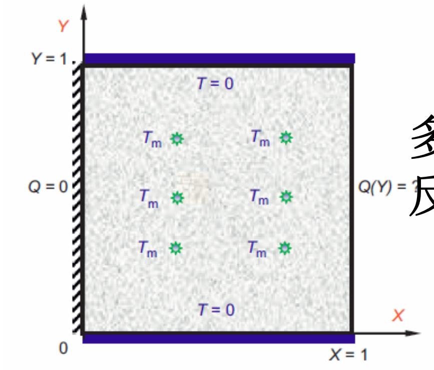


Fig. 1. Physical model and geometry.

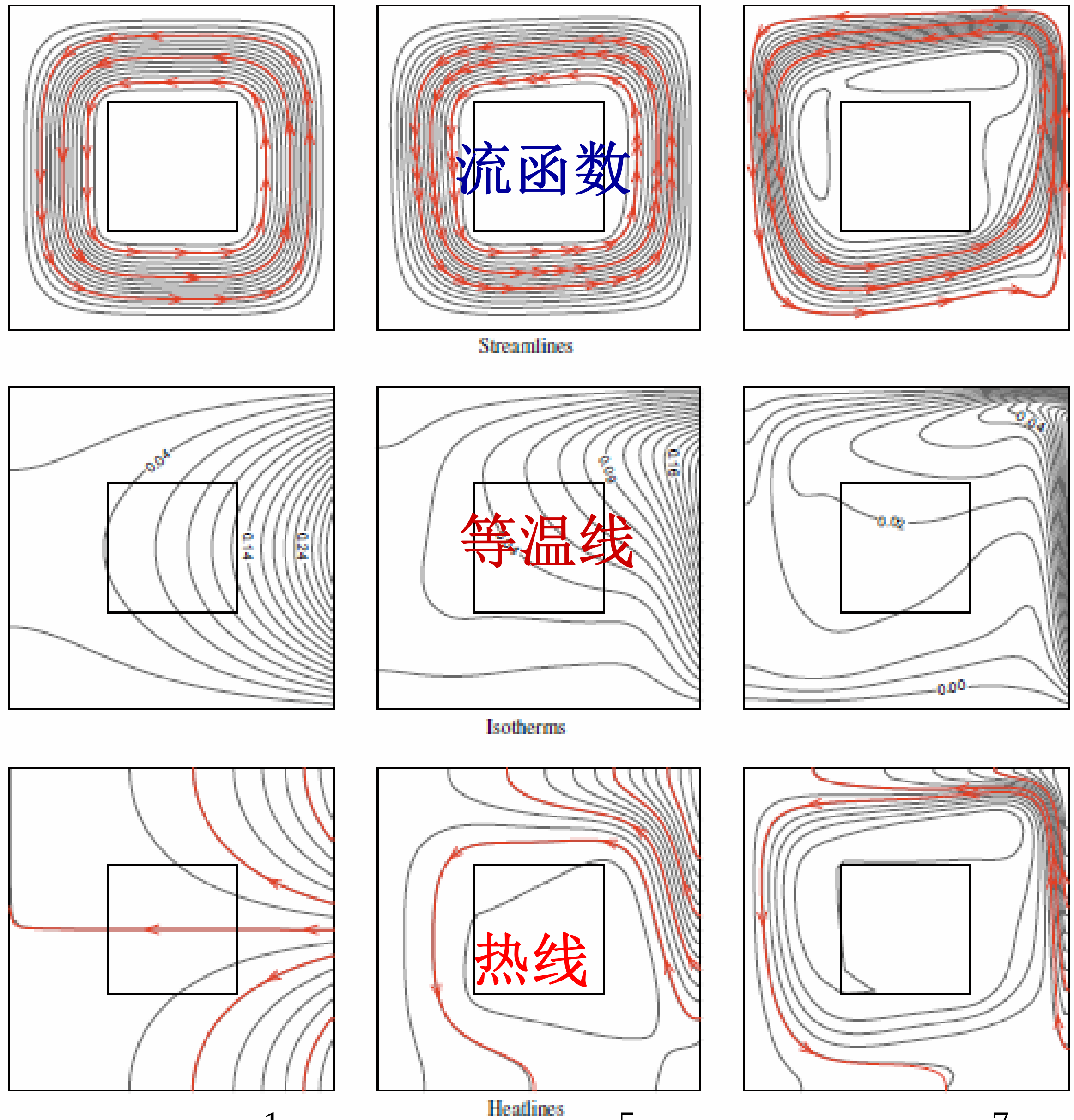
含旋转圆柱混合对流（64）



含孤立体反问题（63）

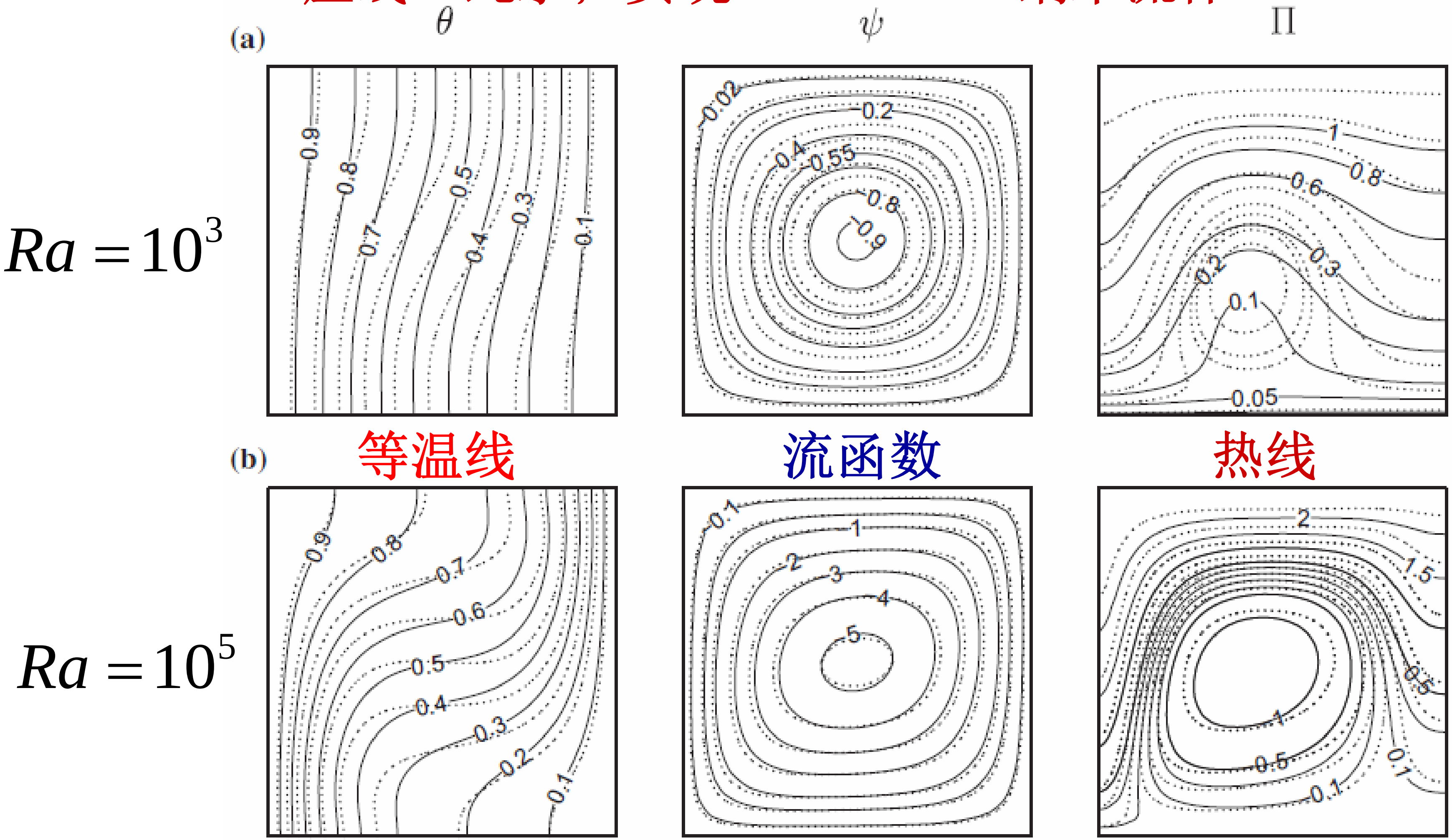


多孔介质反问题（76）



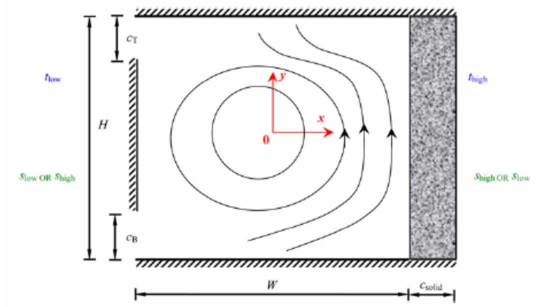
$Ra = 10^1$ $Ra = 10^5$ $Ra = 10^7$

虚线---纯水；实现---Cu-Water纳米流体

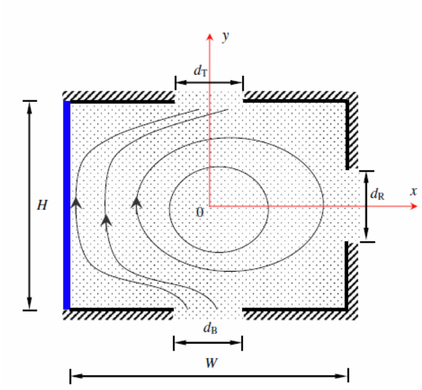


ϕ=0.1 纳米流体空腔自然对流等温线，流函数线及热线（23）

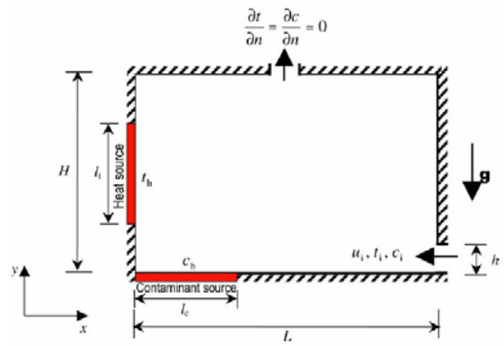
3.2.2 二维开口空腔混合对流问题热传递路径的可视化



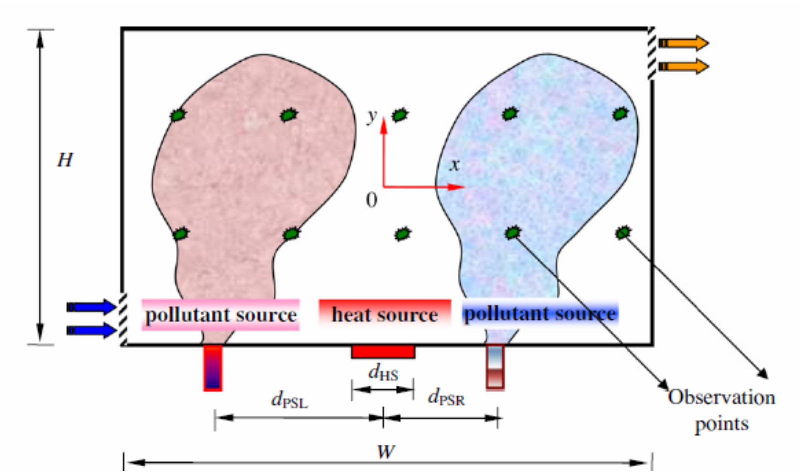
自然通风热湿对流（44）



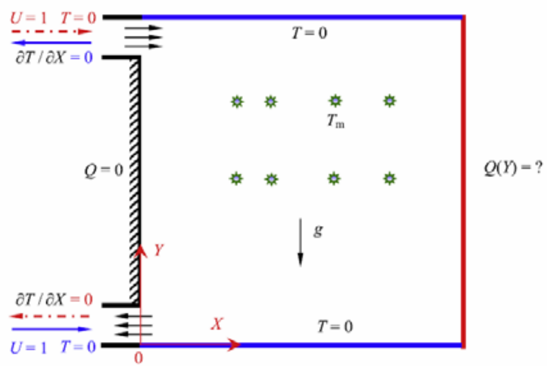
多出口热湿对流（59）



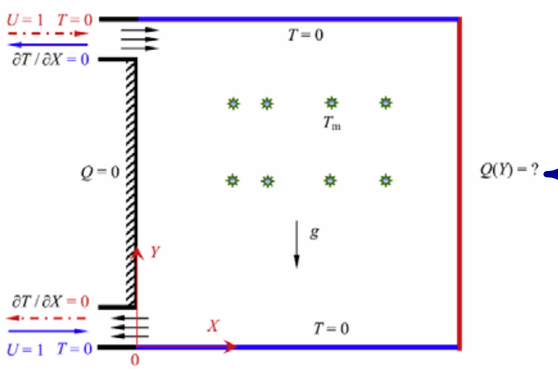
质热传递（99）



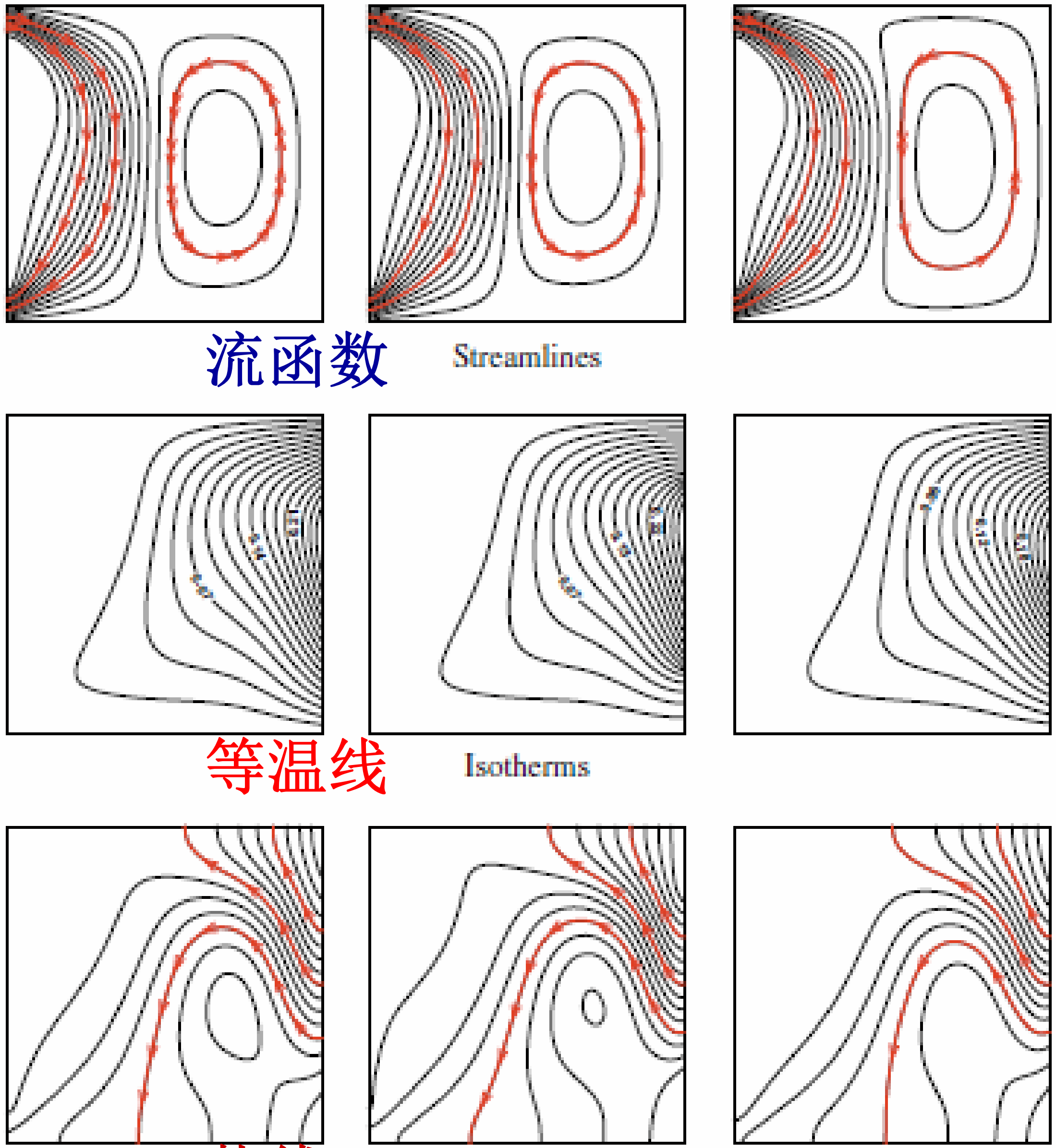
多出口热污染物对流（34）



反问题（27,69）

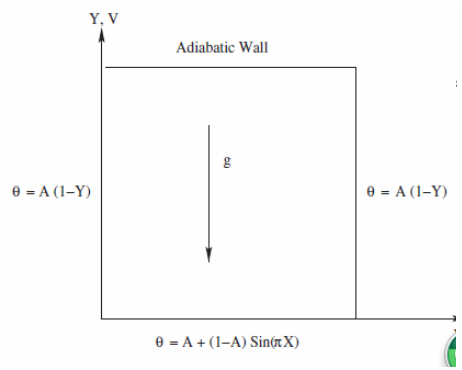


反问题（69）

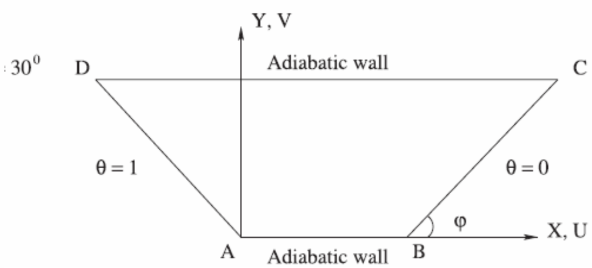


(a) HFP1 (b) HFP2 (c) HFP3

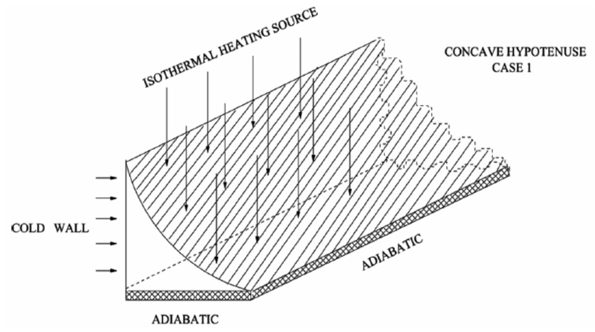
3.2.3 二维空腔多孔介质对流问题热传递路径的可视化



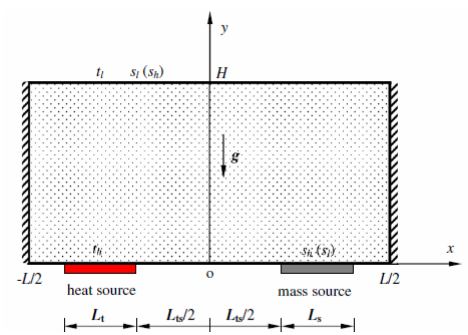
方腔多孔介质热对流（18,24,45）



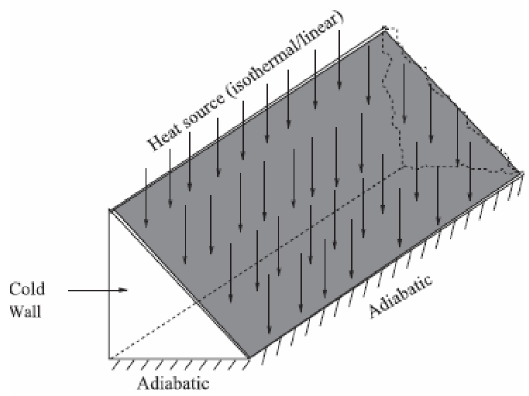
梯形空腔多孔介质对流（2,21）



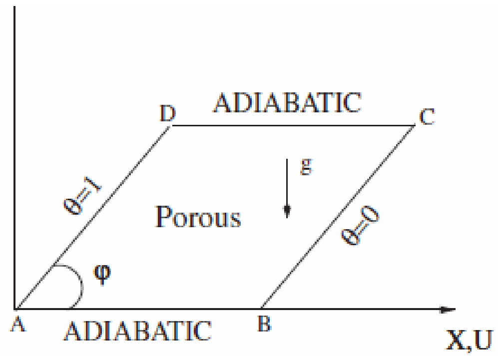
凹面空腔多孔介质（10）



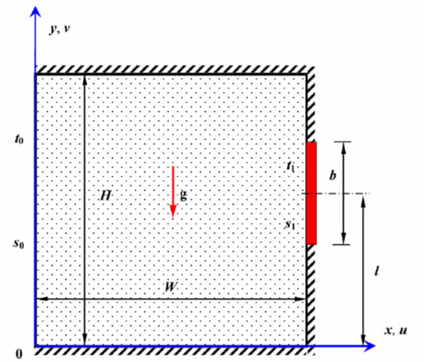
多孔介质热质对流（82）



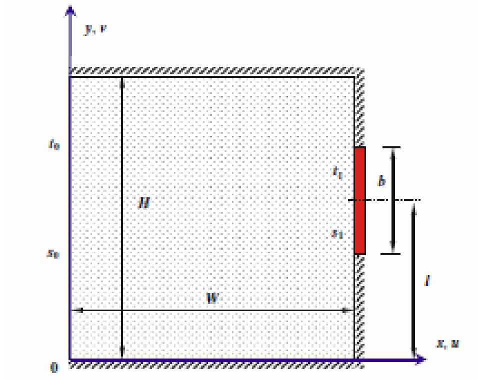
三角形（41）



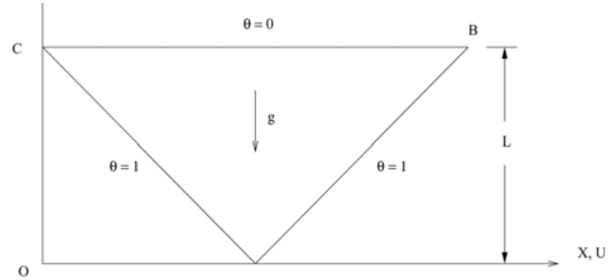
菱形空腔多孔介质自然对流（20）



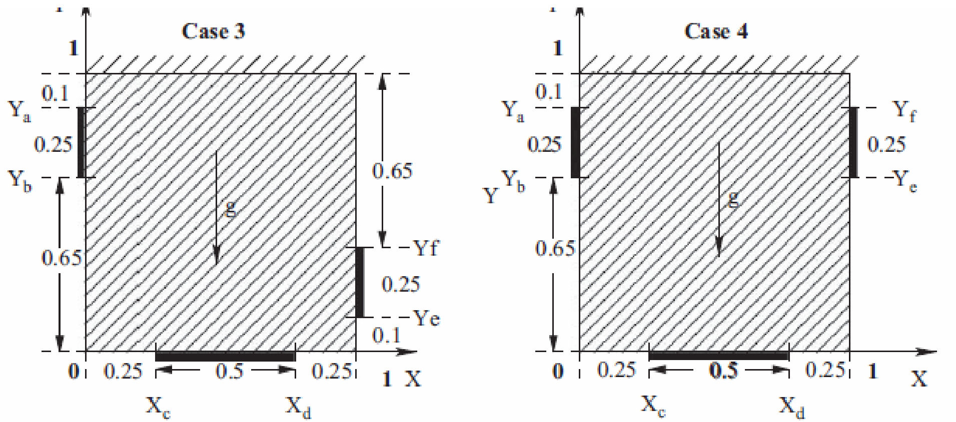
多孔介质
热源离散
（84）



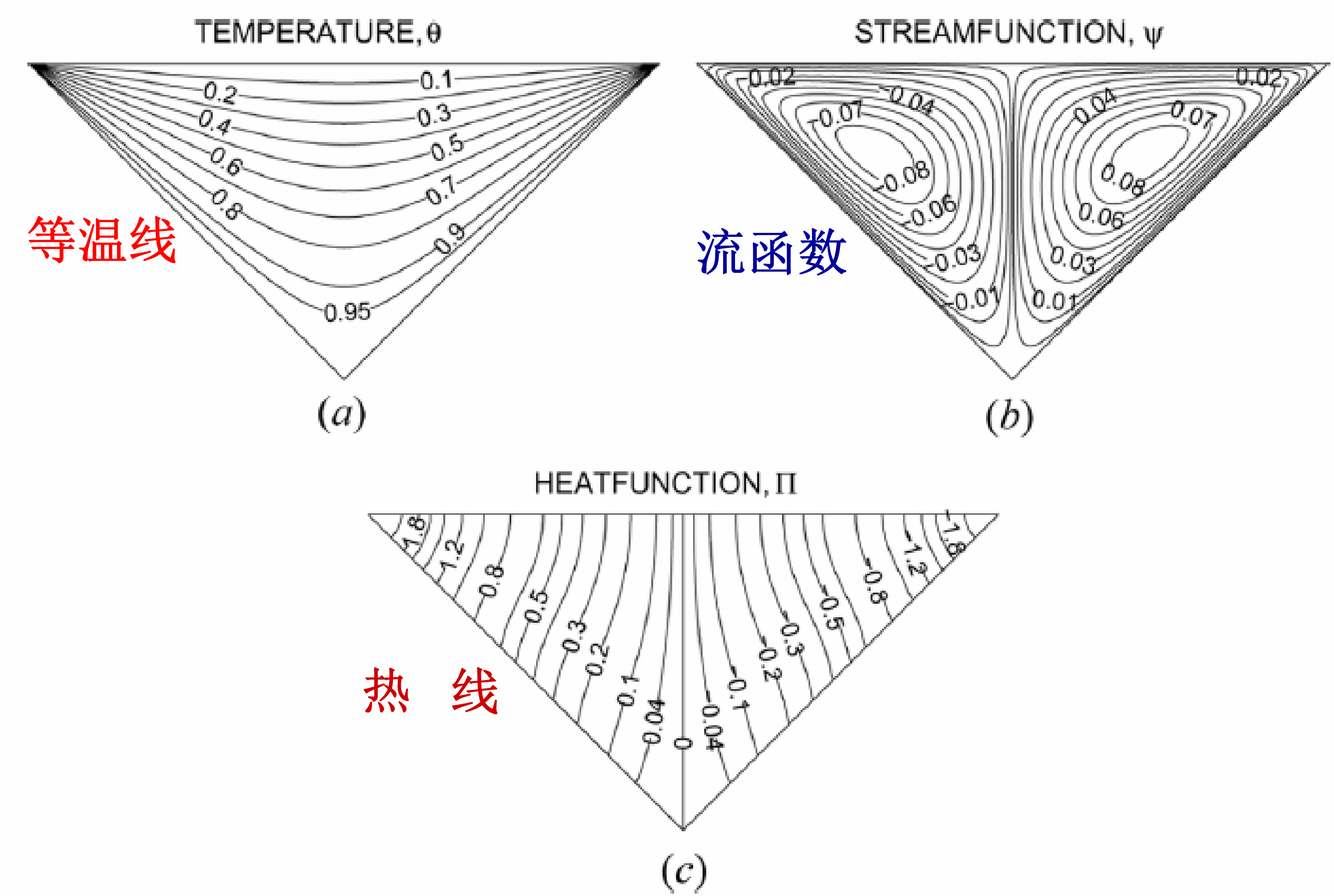
多孔介质热
溶剂对流
（85,87）



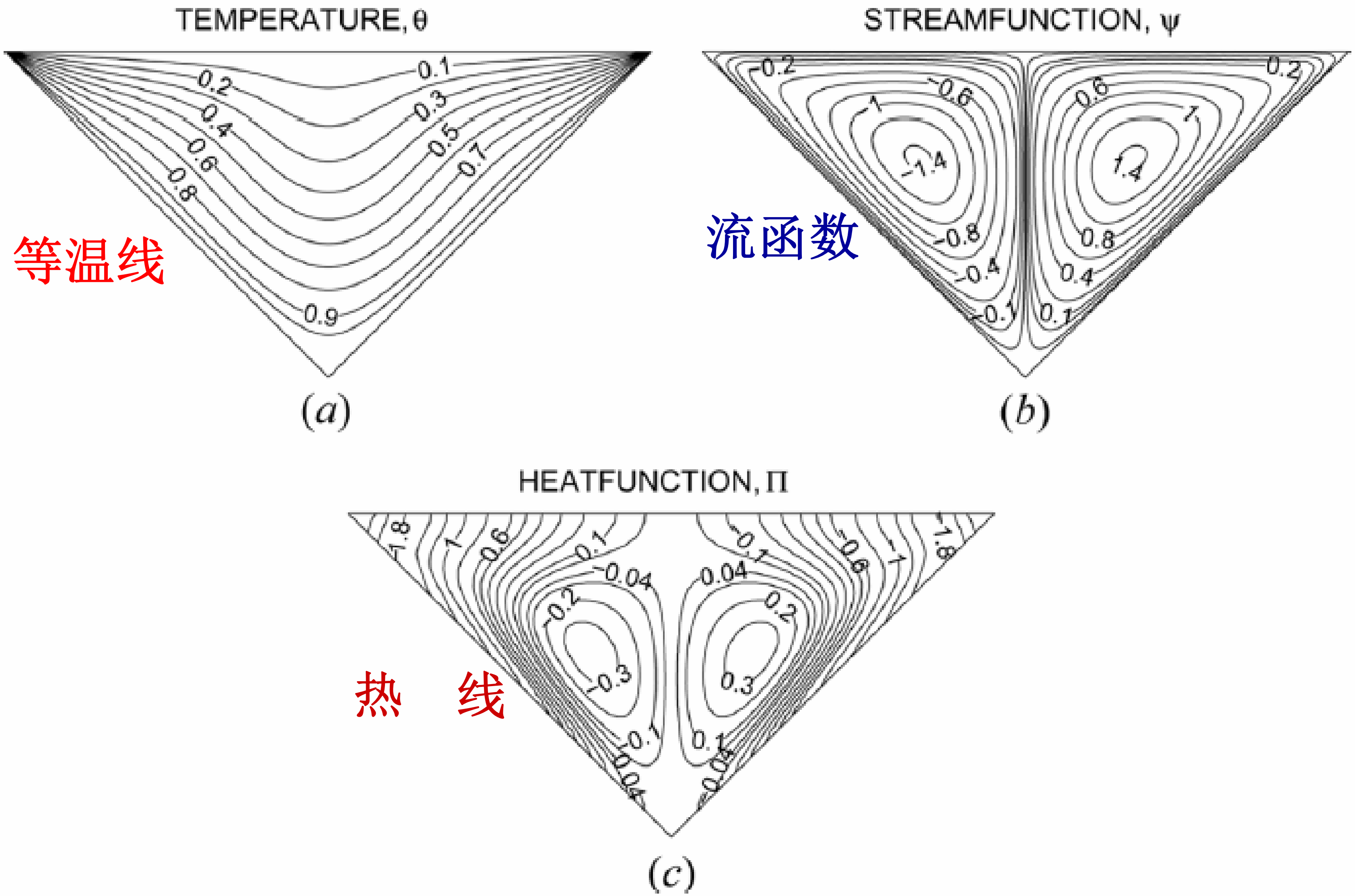
三角形多孔介质
（67）



多孔介质分片加热（61）

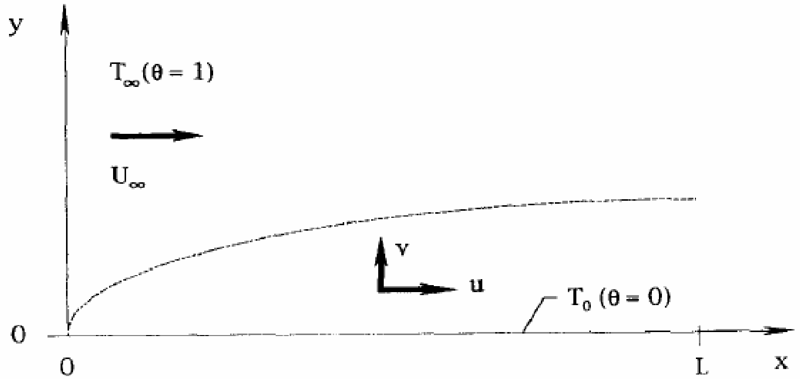


$$Pr = 0.015, Da = 10^{-5}, Ra = 5\times10^{5}$$

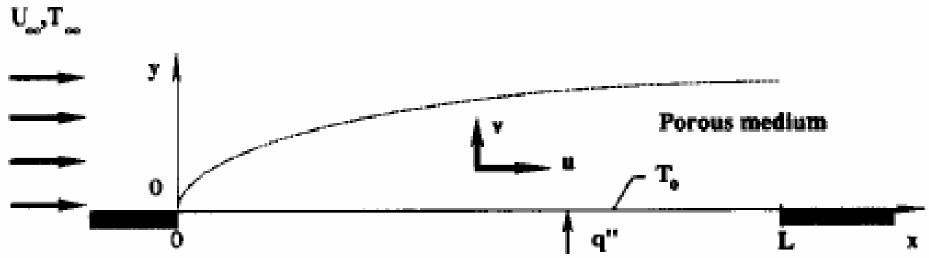


$$\Pr = 0.015, Da = 10^{-4}, Ra = 5 \times 10^{5}$$

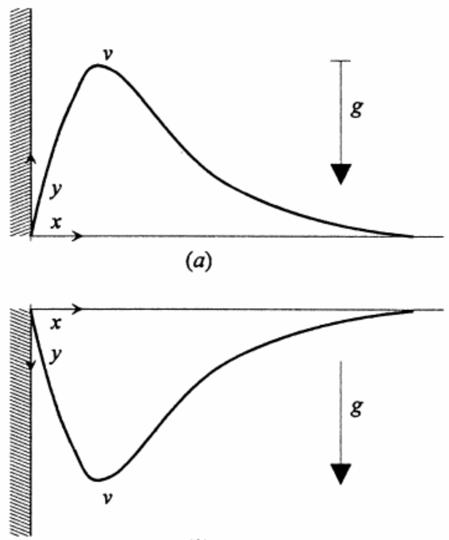
3.2.4 二维边界层对流问题热传递路径的可视化



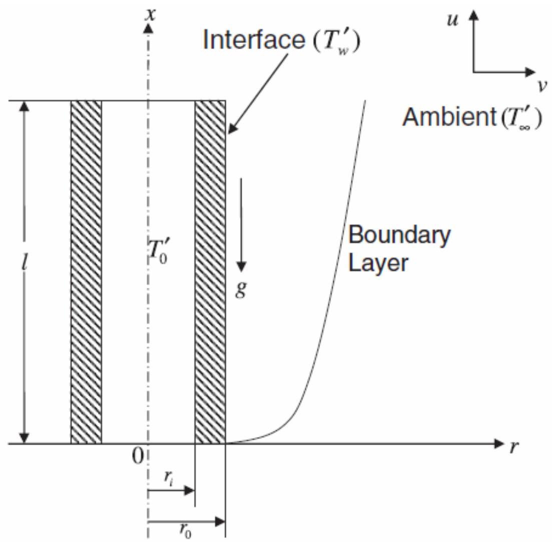
二维平板边界层(116)



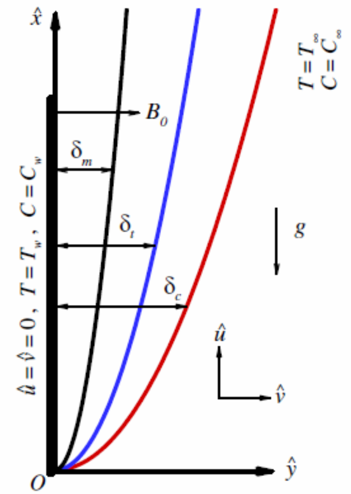
二维多孔介质边界层(115)



二维竖壁上自然对流
(115)

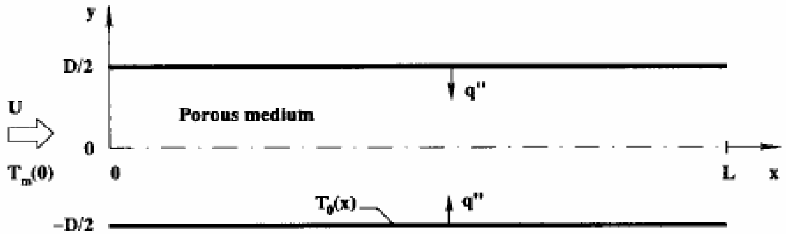


二维细长圆柱外
边界层(9)

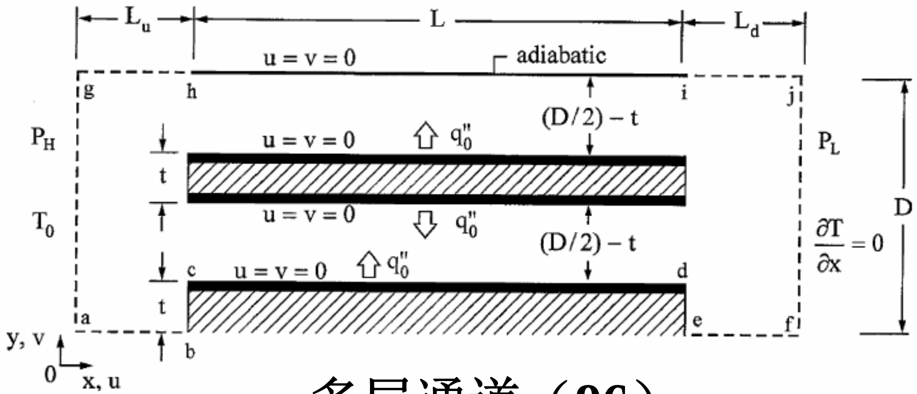


有横向磁场力热质
耦合边界层流动(11,26)

3.2.5 二维强制对流问题热传递路径的可视化

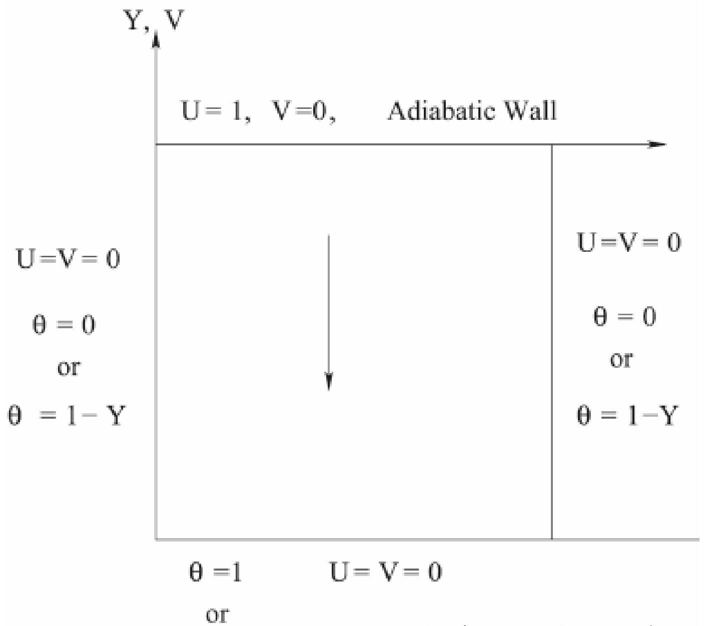


多孔介质通道(115)

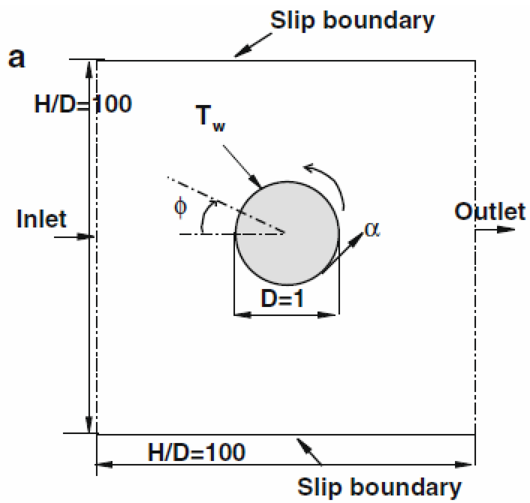


多层通道（96）

反应流



顶盖驱动混合对流（29,42）



通道内旋转圆柱（71）

3. 3 热线概念提出后20余年学界的评价

3.3.1 土耳其学者Costa的评价

Costa 在热线概念提出23年后在ASME Applied Mechanixs Review上撰文对热线的概念做了比较公允的评价（95）：

Heatlines and masslines are, in fact, the most adequate tools for visualization and analysis of two-dimensional convective heat and/or mass transfer. They give the paths followed by energy and/or mass, which is a picture that cannot be directly obtained from the isotherms and/or isoconcentration lines in convection problems.

(95) Costa, V.A.F., Bejan’s heatlines and mass lines for convection visualization and analysis, ASME J. Applied Mechiancs Review, 2006, 59:126-145

The method was invented two decades ago. It has evolved, and is now mature and ready to be used as a systematic analysis tool. The streamline, heatline, and massline methods can be treated through common procedures, which can be easily implemented in CFD packages, both for convective heat and/or mass transfer in isotropic or in anisotropic media. The last is the application of the method to reacting flows, which considerably enlarges the applicability range of these useful tools.

3.3.2 澳大利亚学者的评价：

澳大利亚Queensland大学工程院的Hooman教授（66, 121,123）指出，Heatline虽然可以生动地显示热能传递的路径，但是毕竟需要多求接一个关于H函数的泊桑方程，显著增加计算工作量。他巧妙地利用流线与局部速度的关系：热线的切线就是热能传递的方向，正如流函数的切线是速度方向一样；热线的切线与其法向矢量正交，而热线的法向矢量就是其梯度：

$$grad(H) = \nabla \bullet H = \frac{\partial H}{\partial x}\vec{i} + \frac{\partial H}{\partial y}\vec{j}$$

记切向矢量为 $\vec{E}$ ： $\vec{E} \bullet grad(H) = 0$

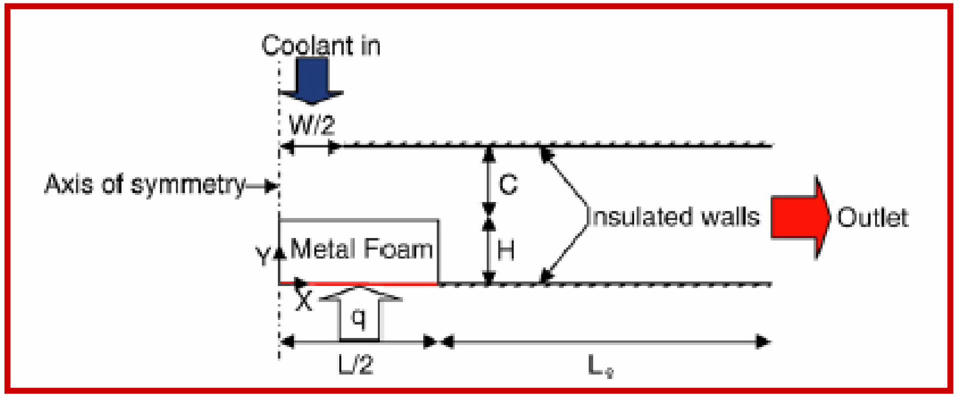
于是得能流矢量$\vec{E}$： $\vec{E}=\frac{\partial H}{\partial y}\vec{i}-\frac{\partial H}{\partial x}\vec{j}$

$$\vec{E}=\underbrace{(\rho u c_p T-k\frac{\partial T}{\partial x})\vec{i}}_{x方向总通量}+\underbrace{(\rho v c_p T-k\frac{\partial T}{\partial y})\vec{j}}_{y方向总通量}$$

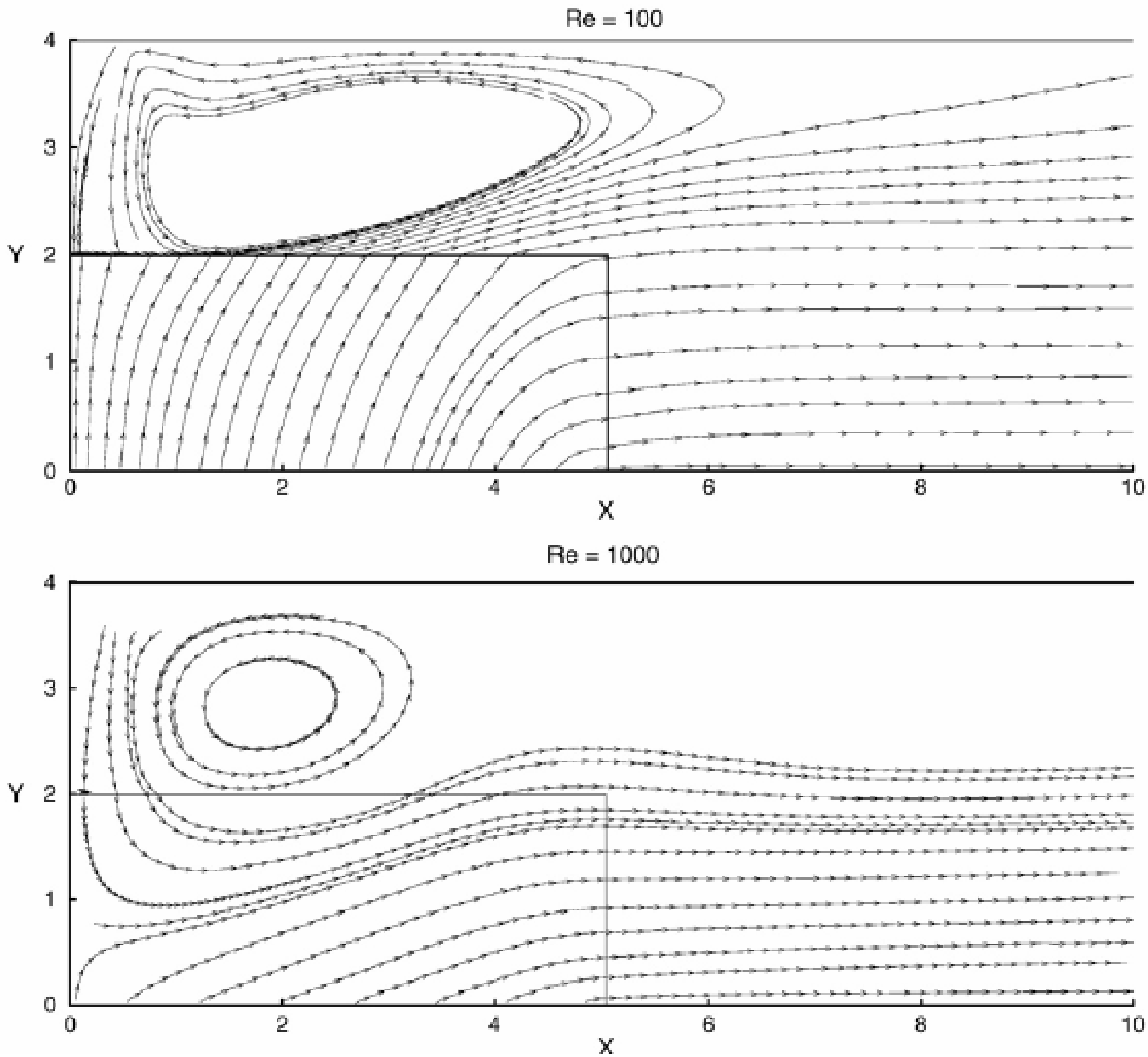
所以利用数值计算得出的速度场温度场，立即可以计算出热线的切向矢量，得出能量传递的路径，根本不用再求解一个关于*H*本身的泊桑方程！

从数值传热学的角度得出能流矢量的方式更加简单！

对于用泡沫金属来强化冲击冷却的情形：



（66）



目　录

1. 缘起

2. 热线 (Heatline) 概念简介

3. 热线概念应用综述

4. 场协同原理应用综述

5. 讨论与结论

Brief Review of HT Enhancement

The enhancement of convective heat transfer is an everlasting subject. Investigations and achievements.

Existing three mechanisms:

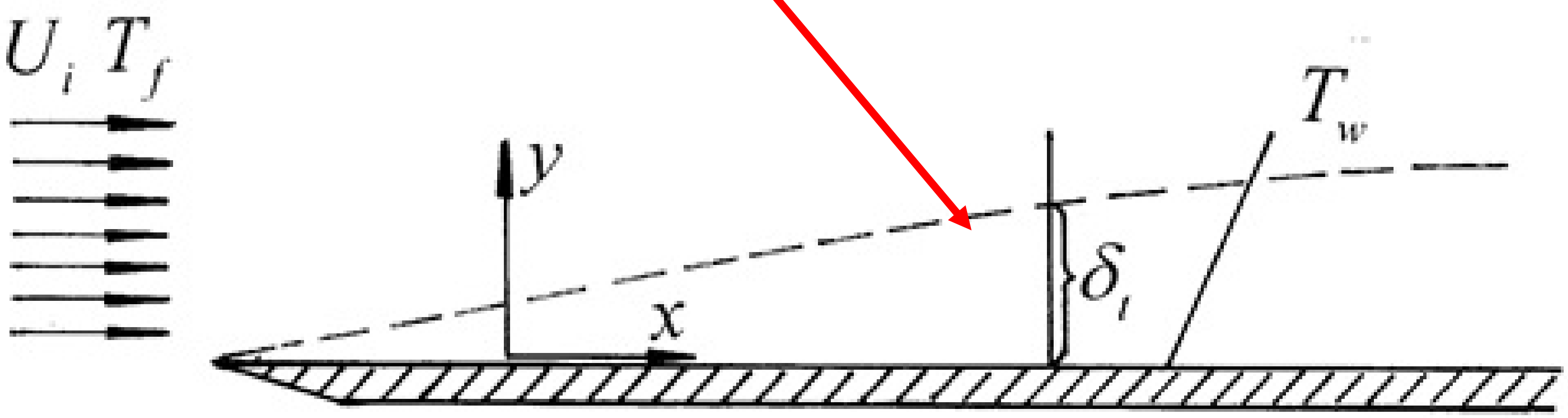
1) Decreasing the thermal boundary layer thickness : off-set fin;
2) Increasing the interruption in the fluids: inserted devices;
3) Increasing the velocity gradient near a heat transfer wall: centre-blocked longitudinal finned tube.

Up to the end of the last century, no unified theory.

Introduction to FSP

In 1998, Prof. Guo: integrating the energy equation along the thermal boundary layer, and noting that

$$(\partial T/\partial y)_{y=\delta_t} = 0$$



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

$$\rho c_p \int_0^{\delta_t} (\vec{U} \bullet gradT)dy = -\left(\lambda\frac{\partial T}{\partial y}\right)_{y=0} = q_w$$

$$\vec{U} \bullet gradT = \left|\vec{U}\right| \left|gradT\right| \cos\theta$$

For a fixed flow rate and temperature difference, the smaller the intersection angle, θ ,the larger the heat transfer rate.

Webster Dictionary : when several actions or forces are cooperative or combined, such situation can be called "synergy".

Thus this idea is called "field synergy (coordination) principle"（FSP）, and the intersection angle the "synergy angle"(included angle).

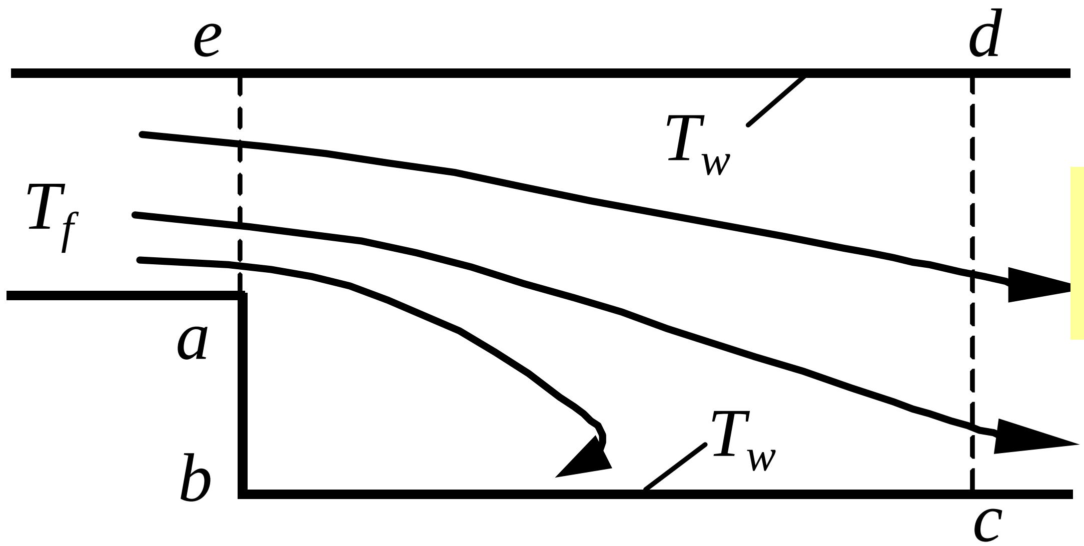
Extension of FSP to Elliptic Flow

Most convective heat transfer processes are of elliptic type .

Extending the FSP to elliptic situations is of great importance.

Integrating 2-D elliptic energy equation in the region of fluid flow and heat transfer over a backward step:

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



Heat transfer over a backward facing step

Using the Gauss theorem for reduction of the integral dimension ;

Noting: a-e and c-d are the boundaries of inlet and outlet in fluids;

The integration leads to

$$\iint\limits_{\Omega_{abcdea}} \rho c_p (U \cdot \nabla T) dxdy - \int\limits_{ae} \vec{n} \cdot \lambda \nabla T dS - \int\limits_{cd} \vec{n} \cdot \lambda \nabla T dS$$

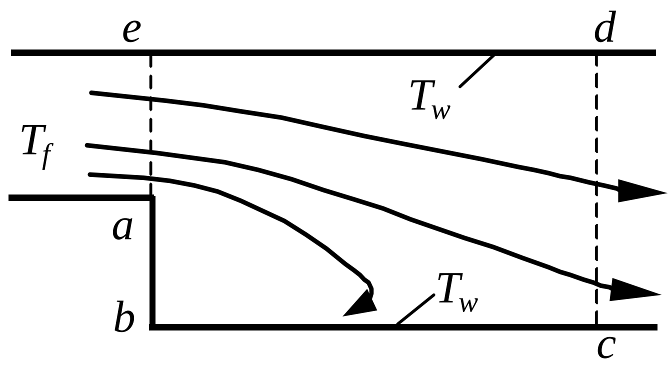
Convective term **Conduction in fluids**

$$= \int\limits_{abc} \vec{n} \cdot \lambda \nabla T dS + \int\limits_{de} \vec{n} \cdot \lambda \nabla T dS = Q_{w,abc} + Q_{w,de}$$

Conduction along solid wall

↓

Convective heat transfer rate



Summary of FSP

"The principle of field synergy for the enhancement of convective heat transfer may be stated as follows: the better the synergy of velocity and temperature gradient/heat flow fields, the higher the convective heat transfer rate under the same other conditions. The synergy of the two vector fields or the three scalar fields implies that **(a) the included angle between the velocity and the temperature gradient/heat flow should be as small as possible** i.e., the velocity and the temperature gradient should be as parallel as possible;

(b) the local values of the three scalar fields should all be simultaneously large, i.e., larger β values of cos should correspond to larger values of the velocity and the temperature gradient; **(c) the velocity and temperature profiles at each cross section should be as uniform as possible. Better synergy among such three scalar fields will lead to a larger value of the Nusselt number”**

Z.Y. Guo, **W.Q. Tao, R.K. Shah, The field synergy (coordination) principle and its applications in enhancing single phase convective heat transfer, International Journal of Heat and Mass Transfer, 48 (2005) 1797–18**

Indication of Synergy Degree

Field synergy number

Come here a question naturally arises: how to judge the goodness of synergy for a specific convective heat transfer? In this regard, two indicators have been proposed: field synergy number and field synergy angle.

When we consider the whole heat transfer process, the field synergy number should be adopted. It can be derived as follows:

Reformulating the boundary layer energy equation into a non-dimensional form with the convective term expressed in vector form, we obtain:

$$Re_x Pr \int_0^1 \left(\overline{U} \cdot \overline{\nabla T} \right) \mathrm{d}\overline{y} = Nu_x$$

Following field synergy number can be defined

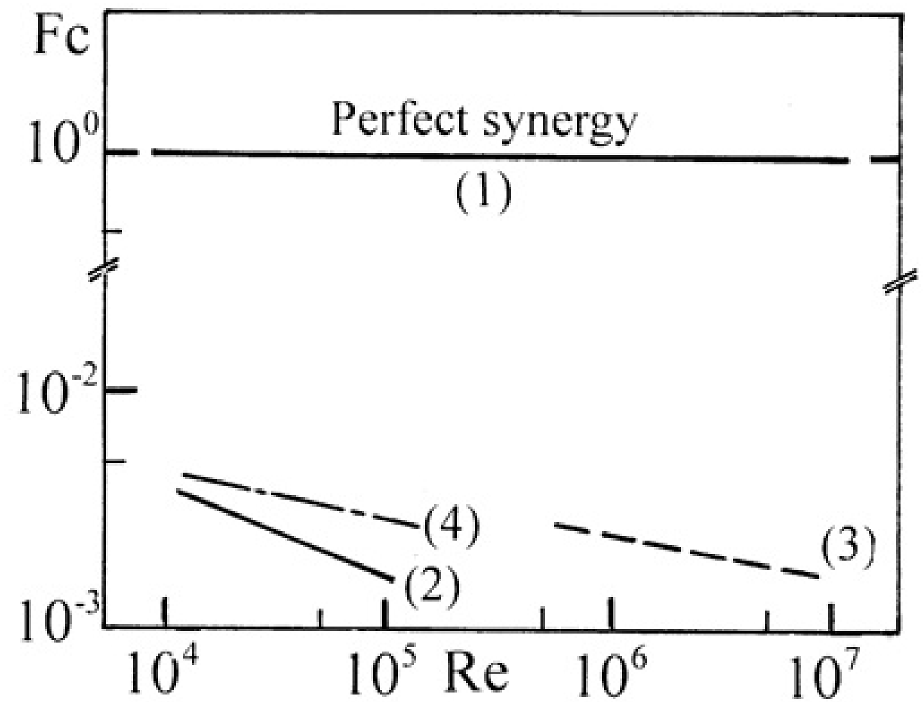
$$Fc = \frac{Nu_x}{Re_x Pr} = \int_0^1 (\overline{U} \cdot \nabla \overline{T}) \, \mathrm{d}\, \overline{y}$$

It can be seen that the maximum upper limit of Fc equals 1, when the velocity vector is in perfect coordination with the temperature gradient, and both dimensionless velocity and temperature gradient are all the way equal to 1 in the boundary layer. In that perfect case we will have:

$$Nu_x = Re_x Pr$$

Or more generally:

$$Nu_x \sim Re_x Pr$$



Field Synergy angle

In the application of FSP, it is often desirable to reveal for an existing heat transfer configuration where the synergy is worse, hence there improvement is needed. In this regard, the local synergy angle is the unanimous one.

To determine the domain averaged synergy angle, several definitions have been tried:

(1) Simple arithmetic mean

$$\theta_m = \frac{\sum \theta_i}{N}$$

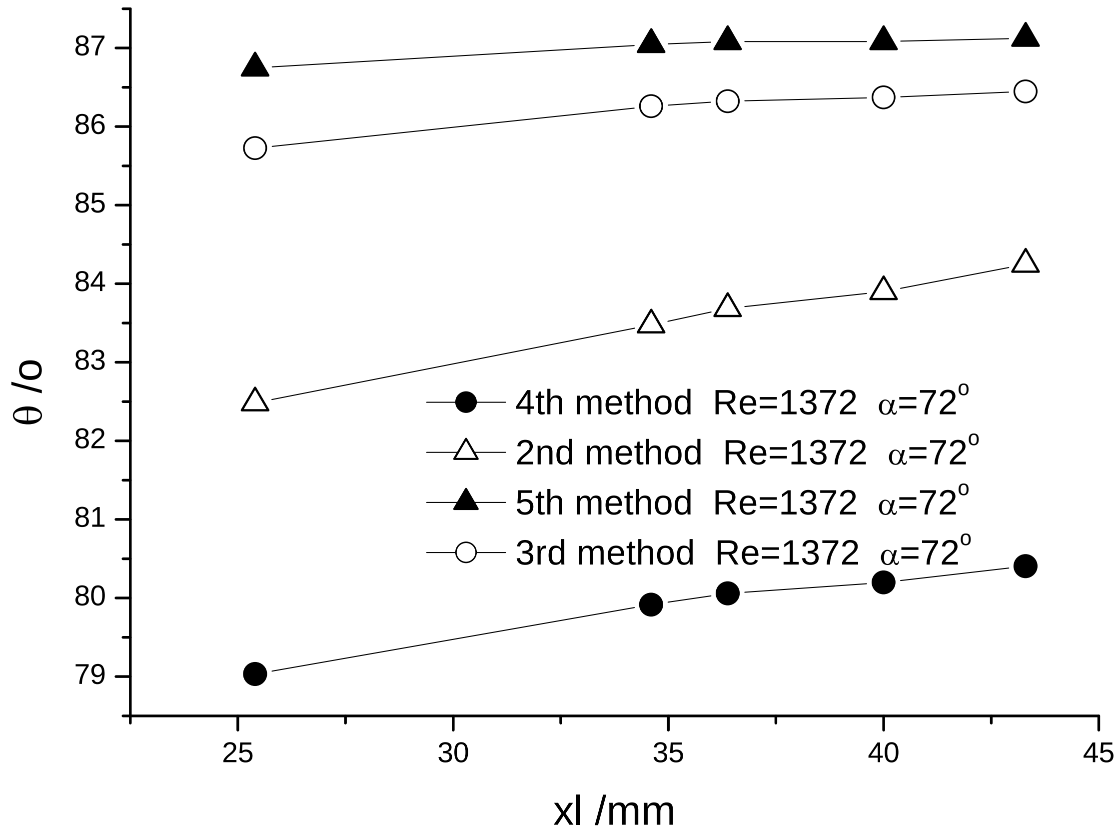
(2) Volume arithmetic mean

$$\theta_m = \frac{\sum \theta_i dV_i}{\sum dV_i}$$

(3) Domain integration mean

$$\theta_m = \arccos \frac{\sum |\vec{u}| \bullet |gradt| \bullet \cos\theta_i \bullet dV}{\sum |\vec{u}| \bullet |gradt| \bullet dV}$$

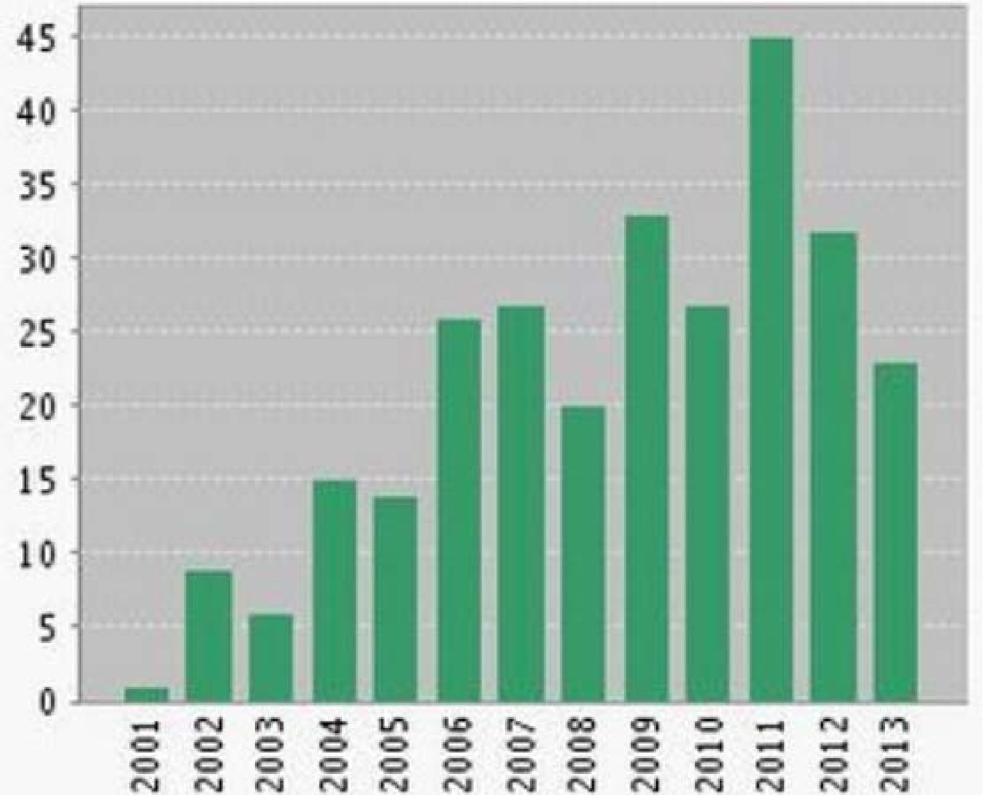
Ya-Ling He, Wen-Quan Tao ,Numerical studies on the inherent interrelationship between field synergy principle and entransy dissipation extreme principle for enhancing convective heat transfer, International Journal of Heat and Mass Transfer 74 (2014) 196–205⇑



Differently averaged synergy angle for slotted fin surface

This gives us quite wide flexibility to adopt a definition for the domain averaged synergy angle: we are interested in is its variation trend and relative magnitude, rather than its absolute value

4. 1 场协同概念提出后学界的发展



2006年以来每年发表与场协同原理（Field synergy/ coordination principle) 有关的文章数量都在20篇以上。

自1998年过增元先生提出后，学界的反应非常热烈，而且有以下发展：

1）从抛物型流动推广到椭圆形流动;

2）推广到非稳态对流换热

3）推广到湍流

4）推广到多孔介质问题

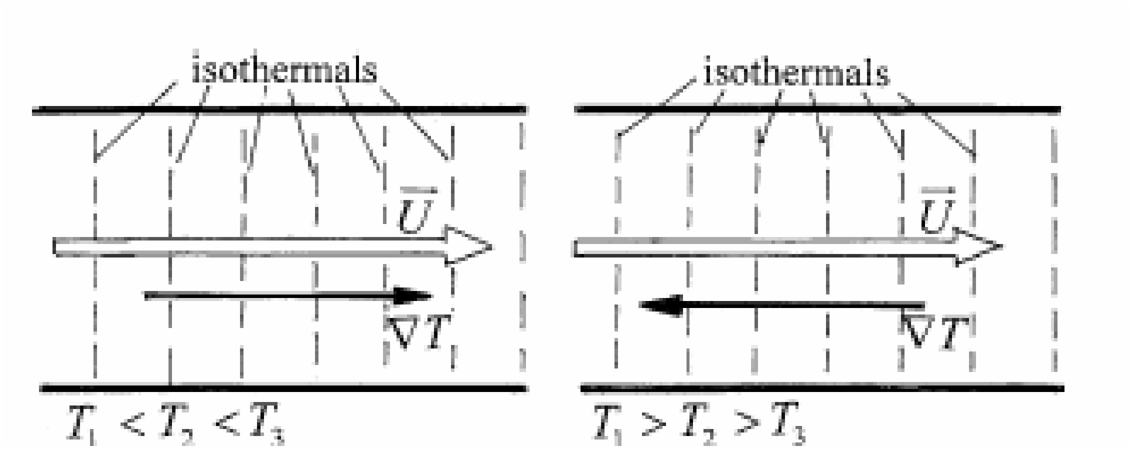
5）推广到可压缩流动

6）推广到各种坐标系

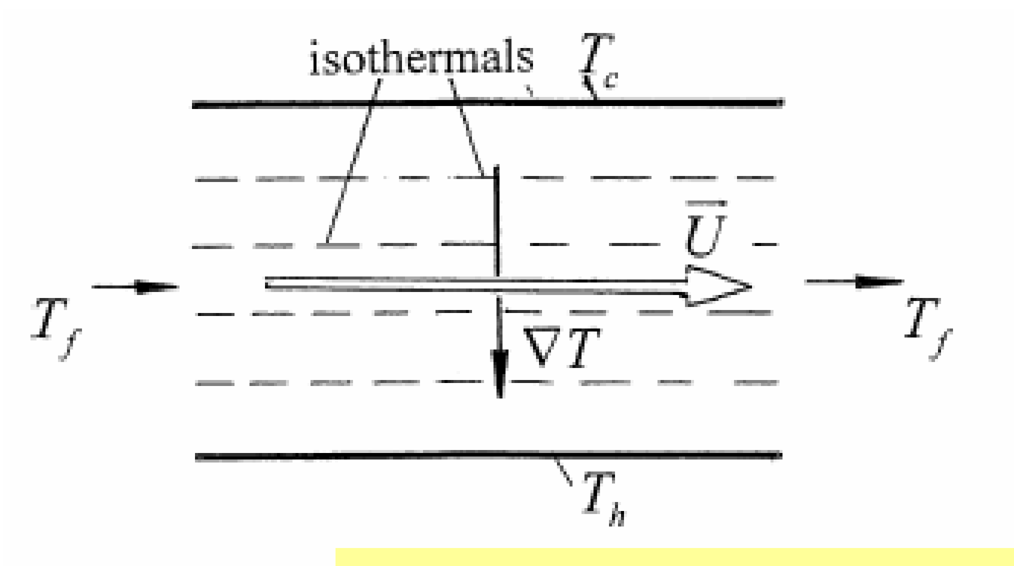
7）推广到化学反应流

8）证明了是各种单相对流强化方式的统一机制。

4. 2 场协同概念提出后学界的试验验证

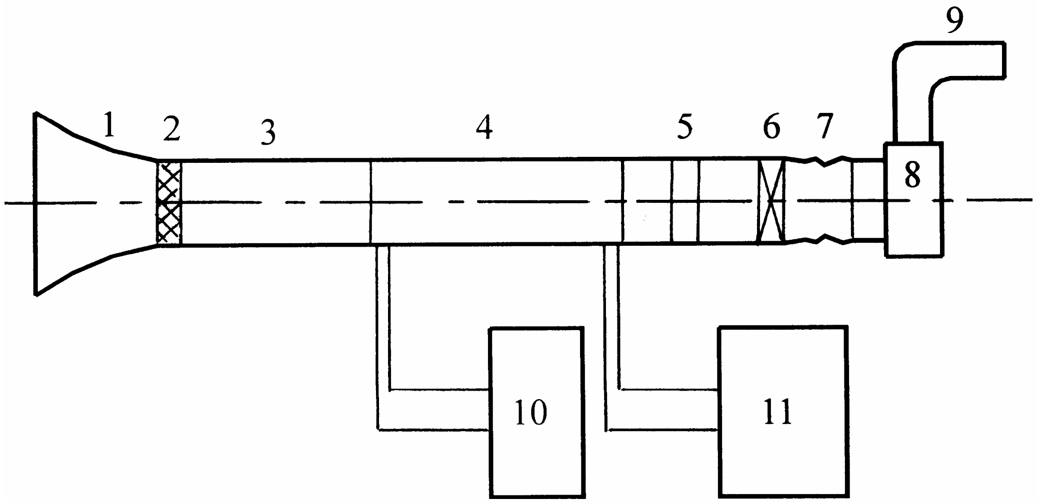


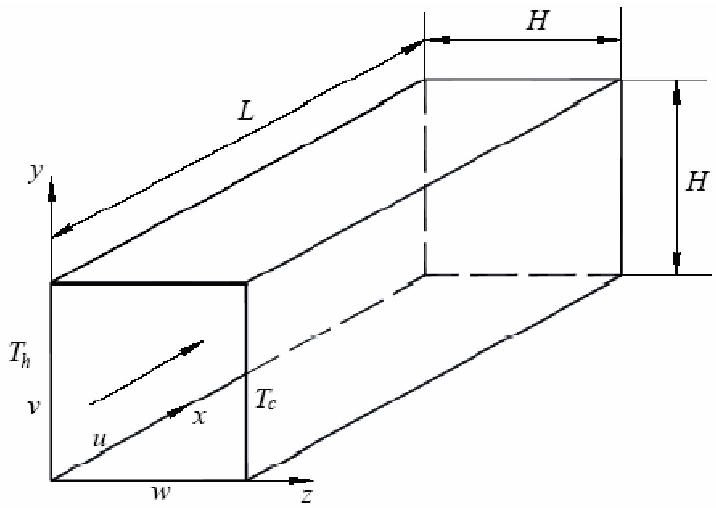
(a) Perfect synergy

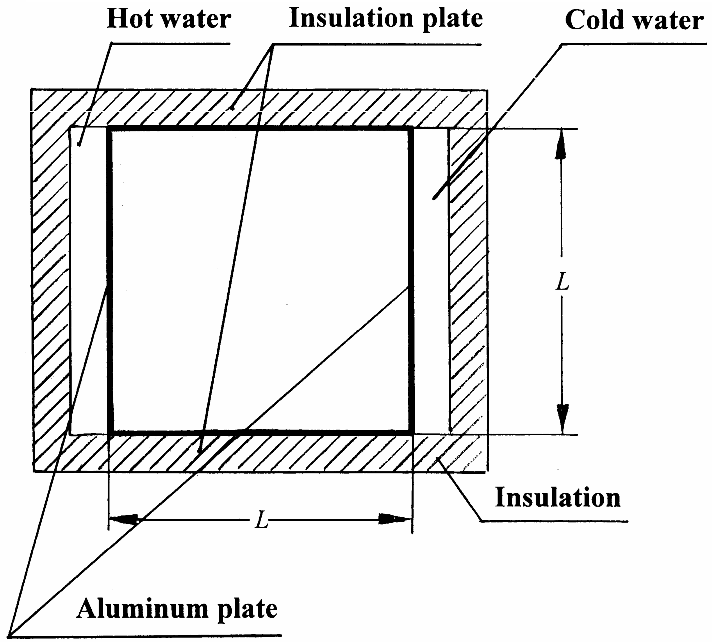


(b) The worst synergy

Two limiting cases of synergy

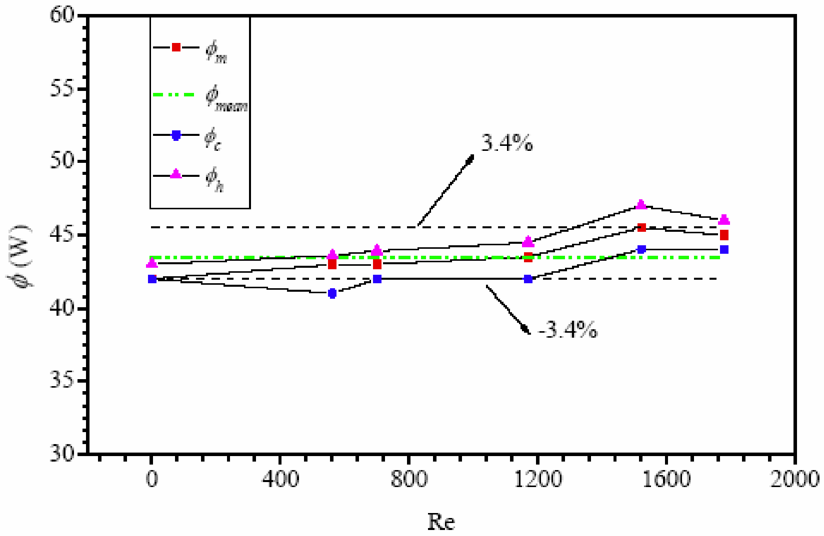




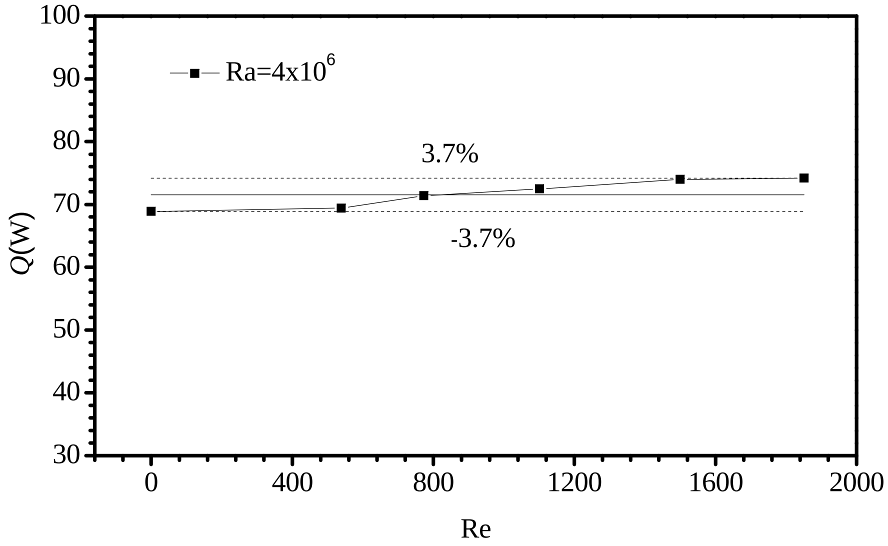


Cross section view of the test duct

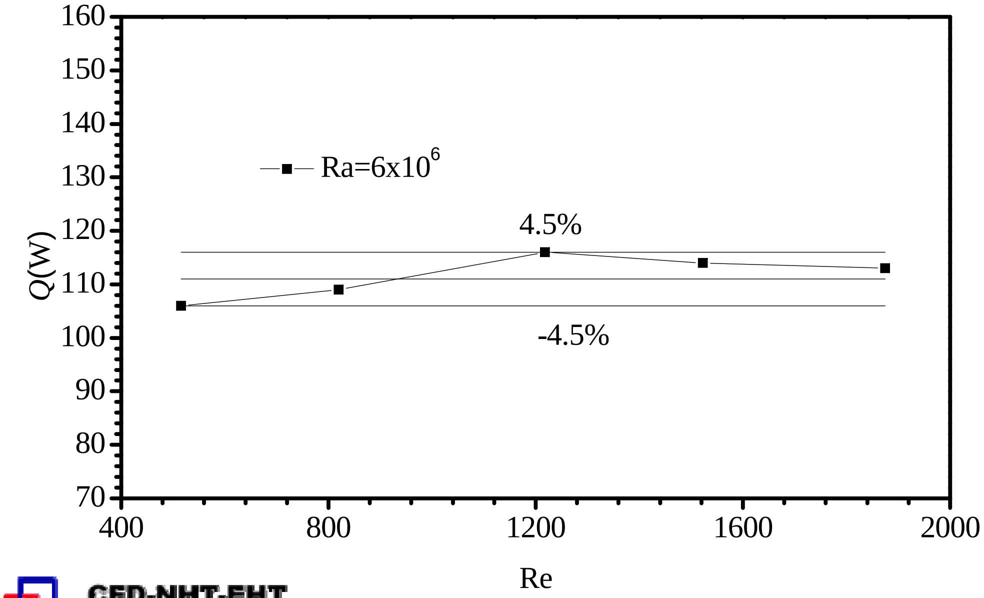
Schematic diagram of the test system



(a) Ra=2x10^6, ΔT=10℃



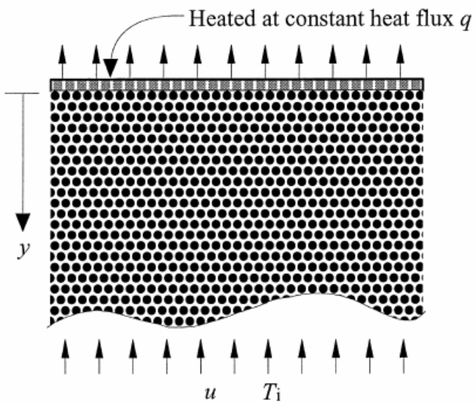
(b) Ra=4x10^6, ΔT=20℃



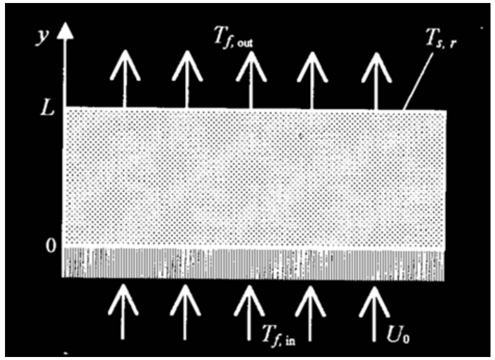
(c) Ra=6x10^6, ΔT=30℃

Fig. Validation test for FSP

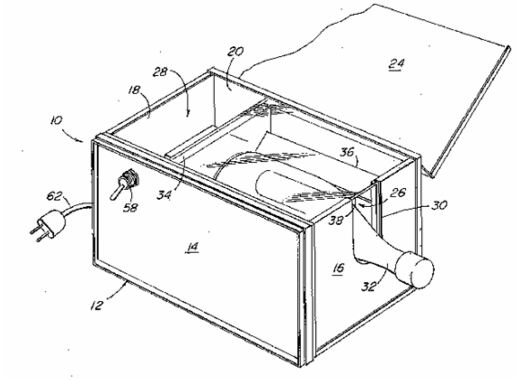
4. 3 场协同概念提出后学界的应用



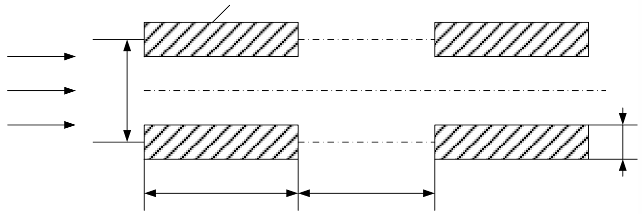
例 1

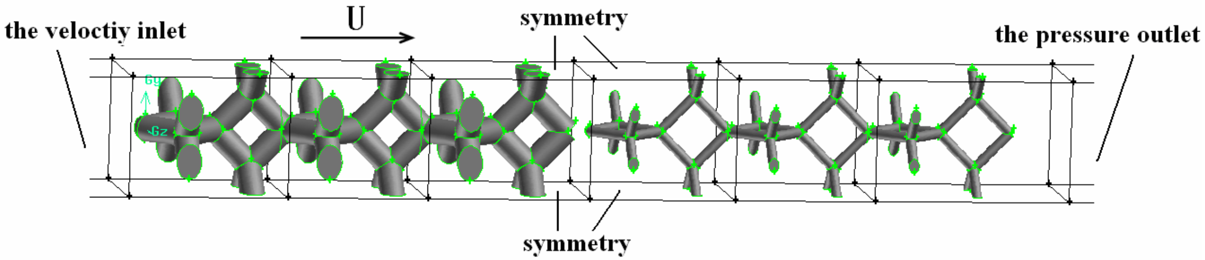


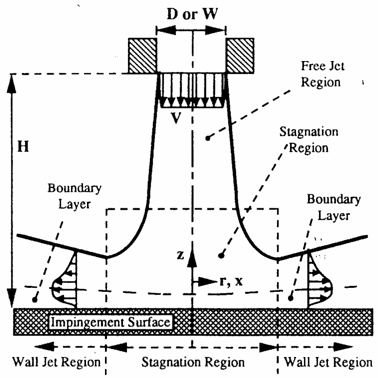
例 2

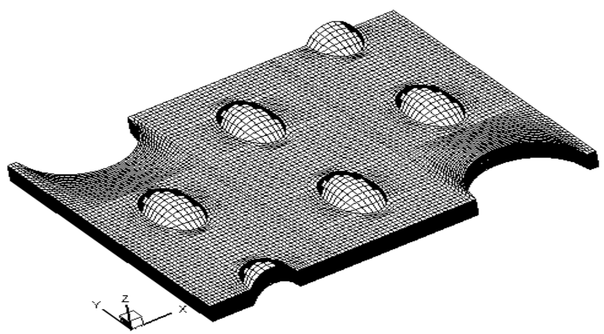


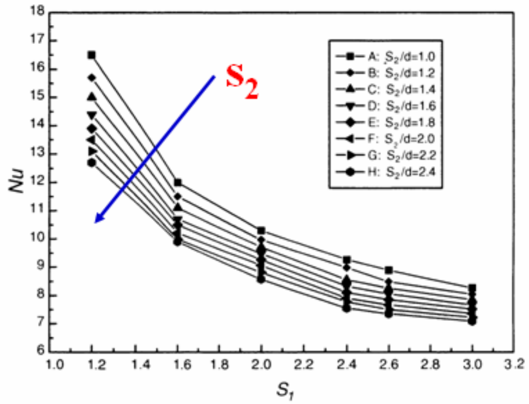
例 3

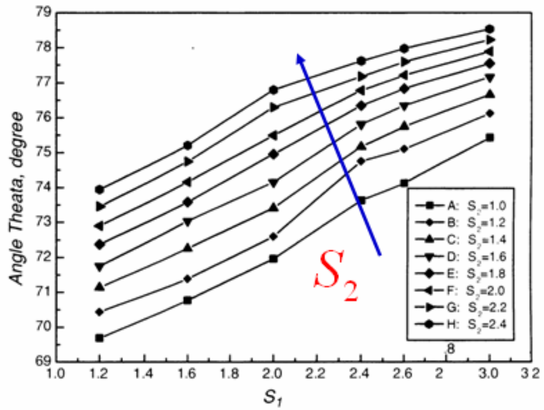


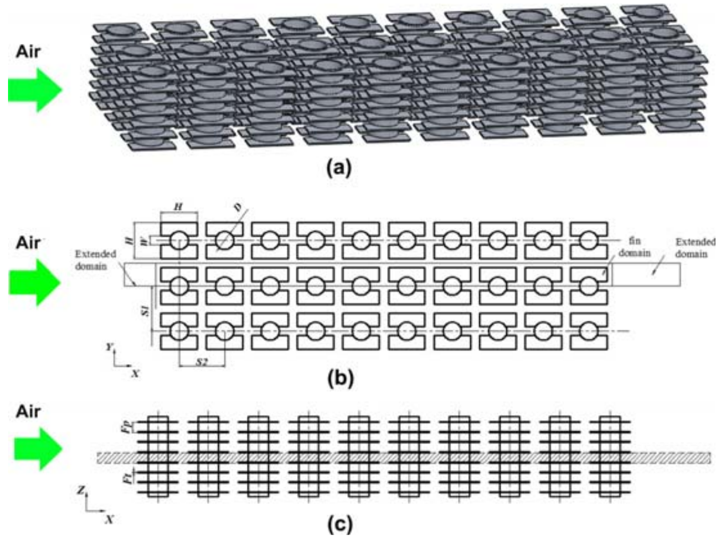


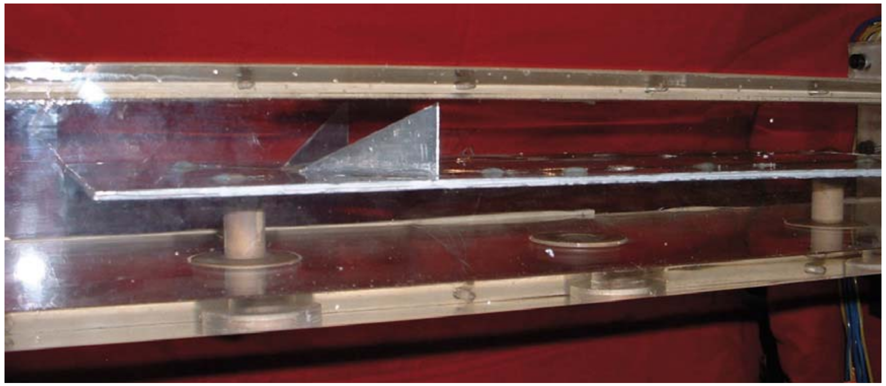


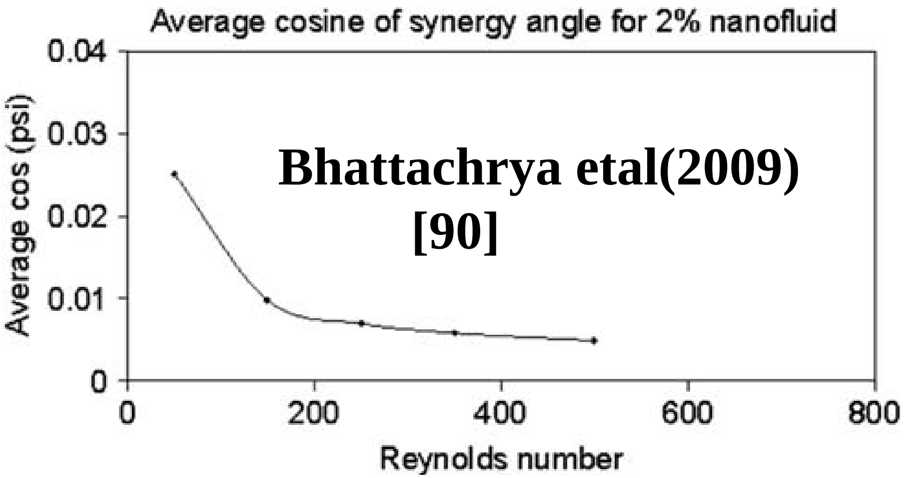


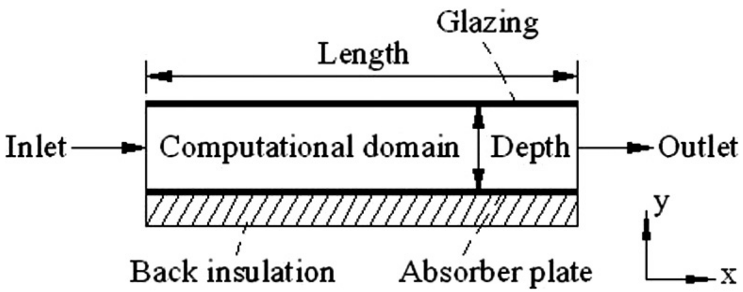

Nu
S_1
S_2
A: S_2/d=1.0
B: S_2/d=1.2
C: S_2/d=1.4
D: S_2/d=1.6
E: S_2/d=1.8
F: S_2/d=2.0
G: S_2/d=2.2
H: S_2/d=2.4

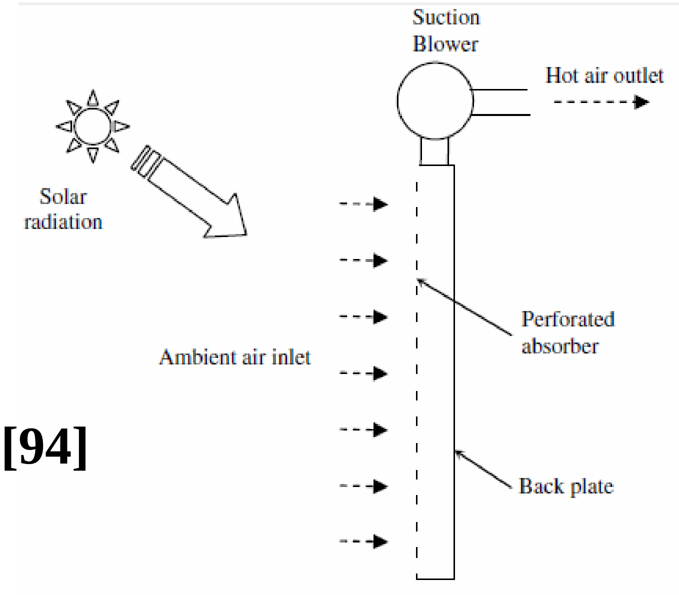

Angle Theata, degree
S_1
S_2
A: S_2=1.0
B: S_2=1.2
C: S_2=1.4
D: S_2=1.6
E: S_2=1.8
F: S_2=2.0
G: S_2=2.2
H: S_2=2.4


Air
(a)
Air
Extended domain
fin domain
Extended domain
(b)
Air
(c)

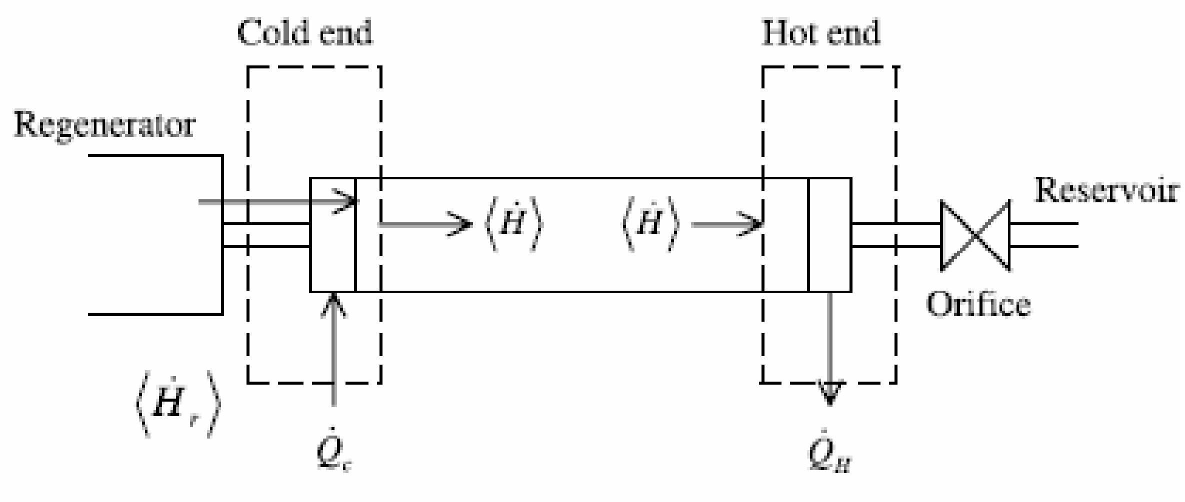



Average cosine of synergy angle for 2% nanofluid
Average cos (psi)
Reynolds number
Bhattachrya etal(2009)
[90]

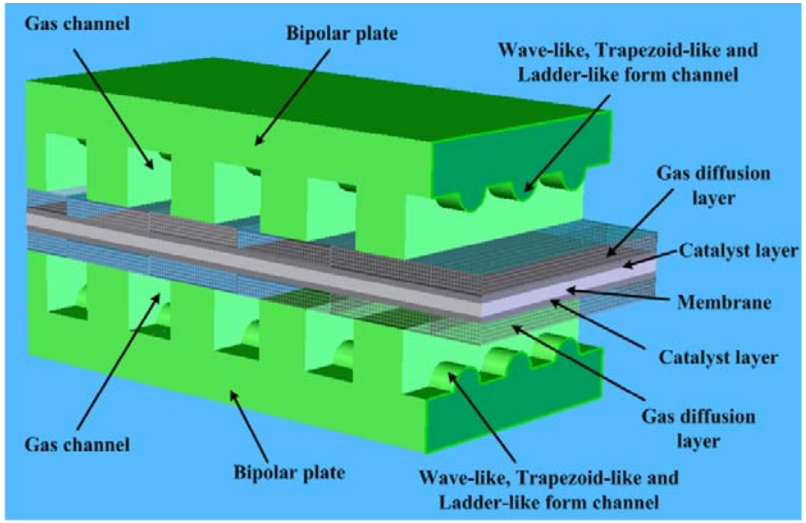




Gao et al (2013) [94]

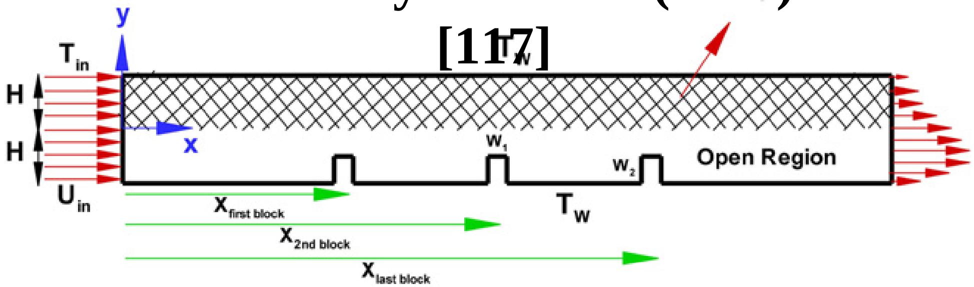


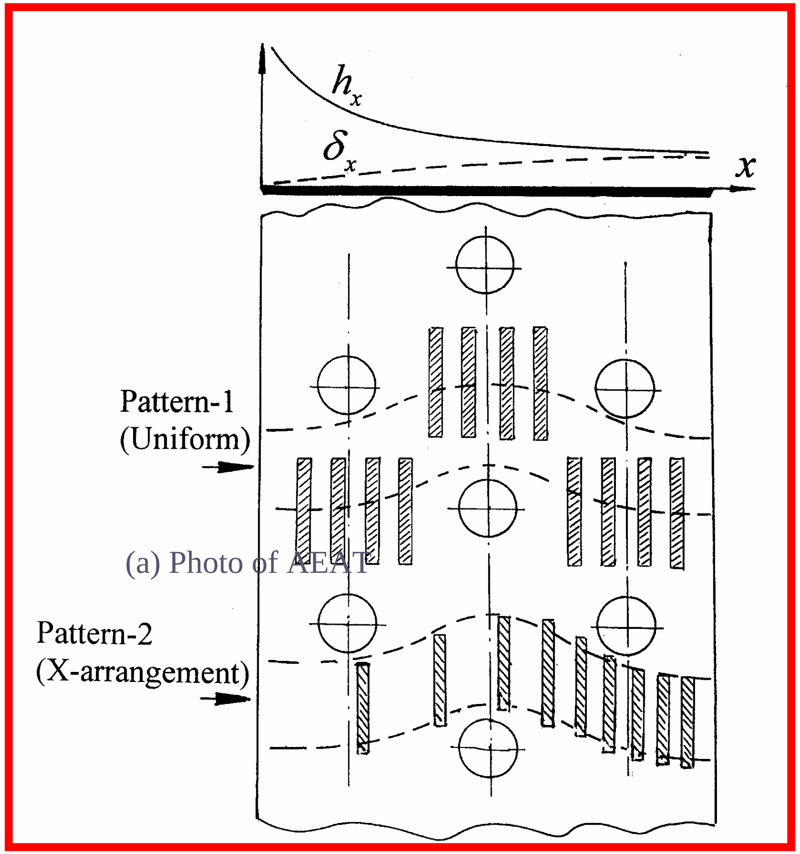
He et al (2004) [95]



台湾大学陈朝光教授
(2008) [117]

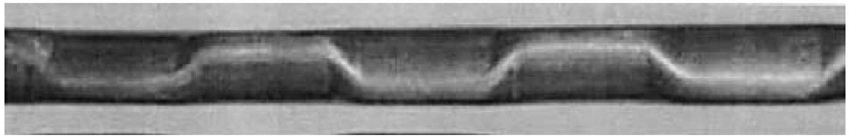
Heidery/Kermani (2013)
[117]

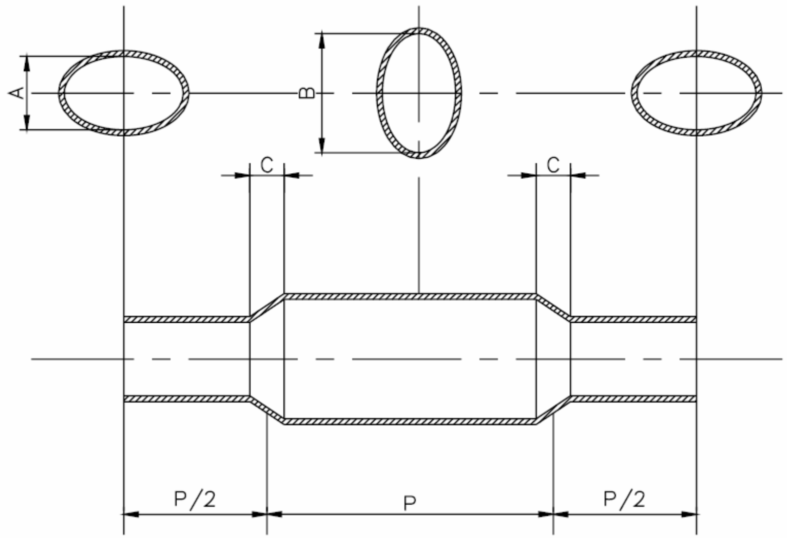




h_x
δ_x
x
Pattern-1
(Uniform)
(a) Photo of AEAT
Pattern-2
(X-arrangement)

例 L1

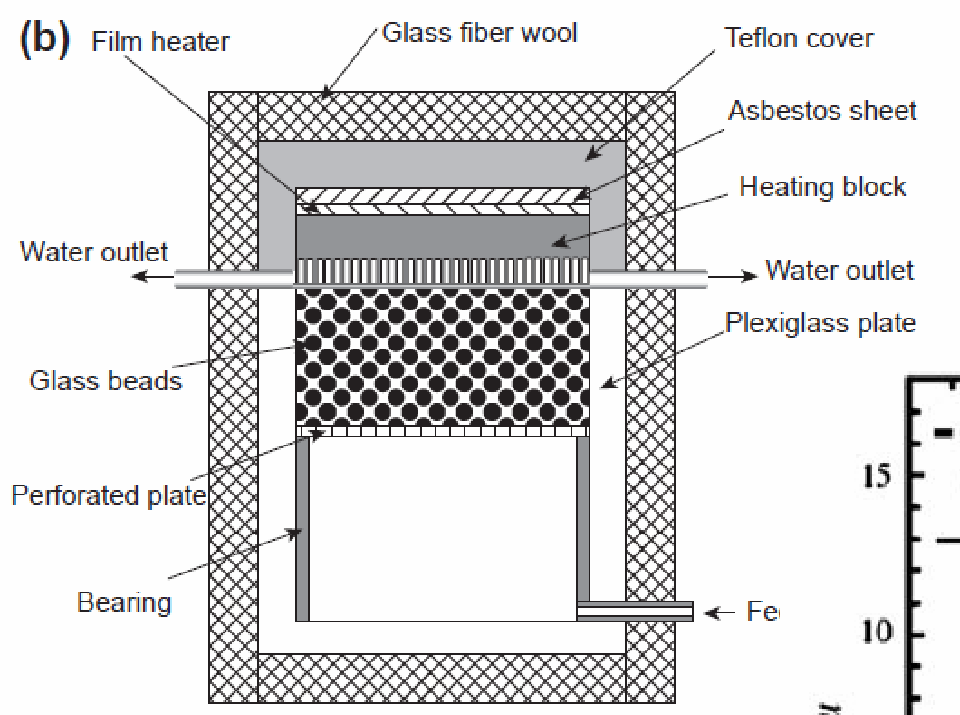




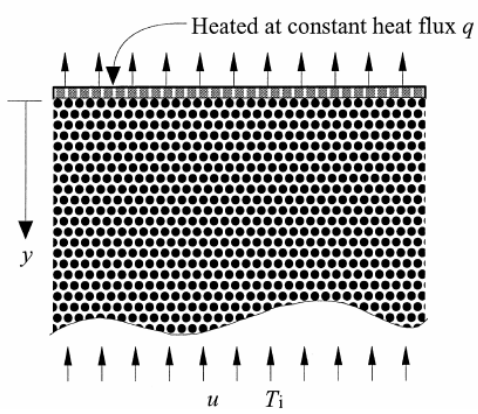
A
B
C
C
P/2
P
P/2

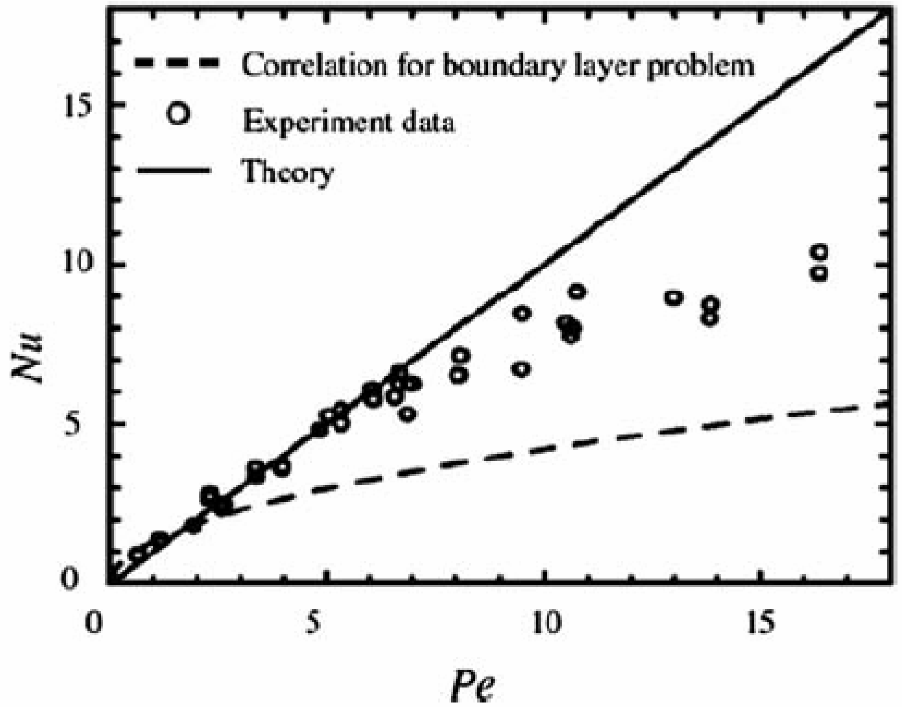
例 L

例 1 说明



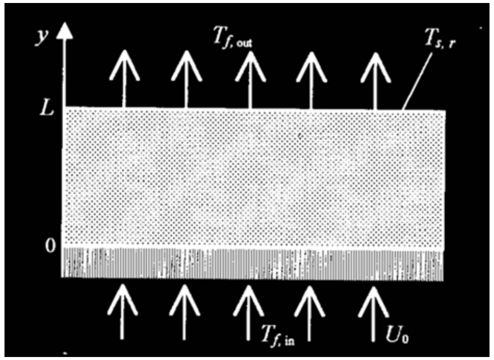
Test facility

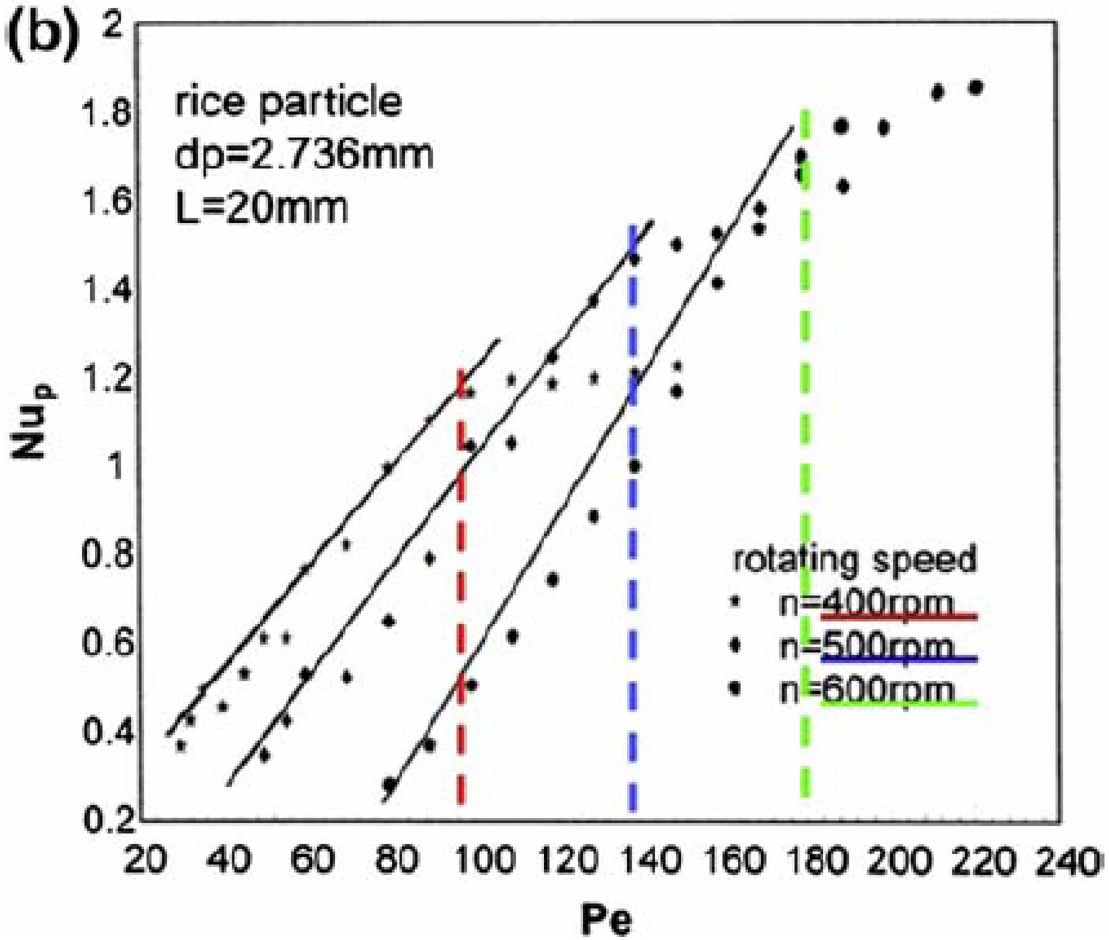




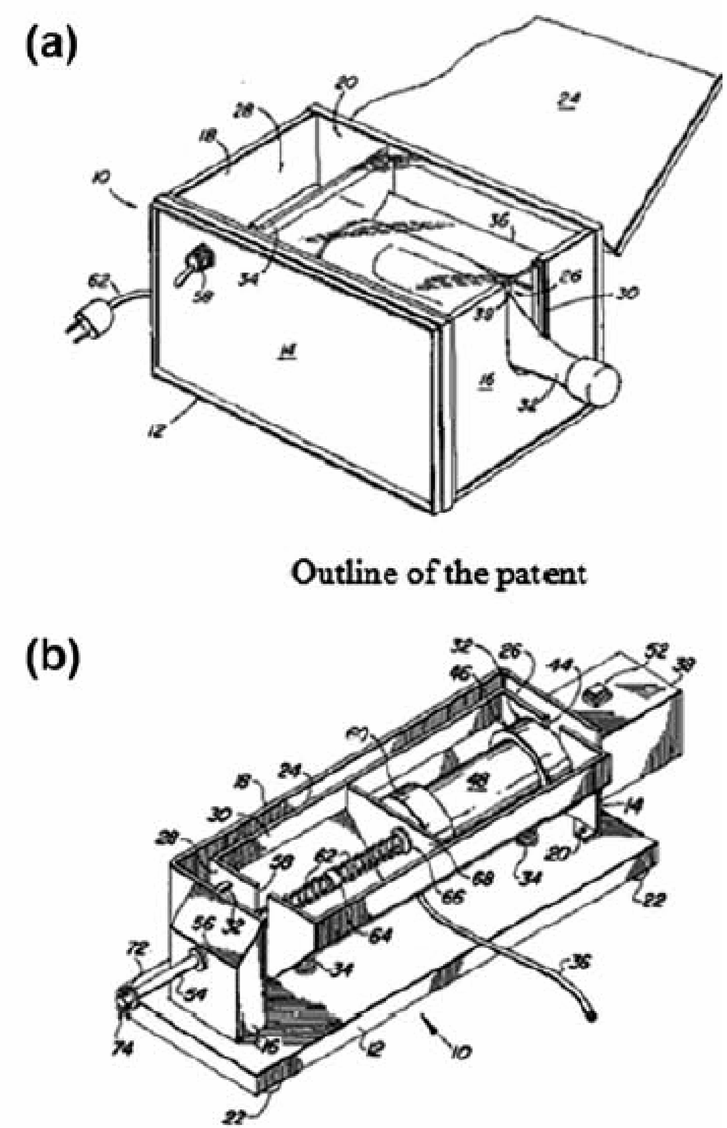
$$Nu = RePr = Pe$$

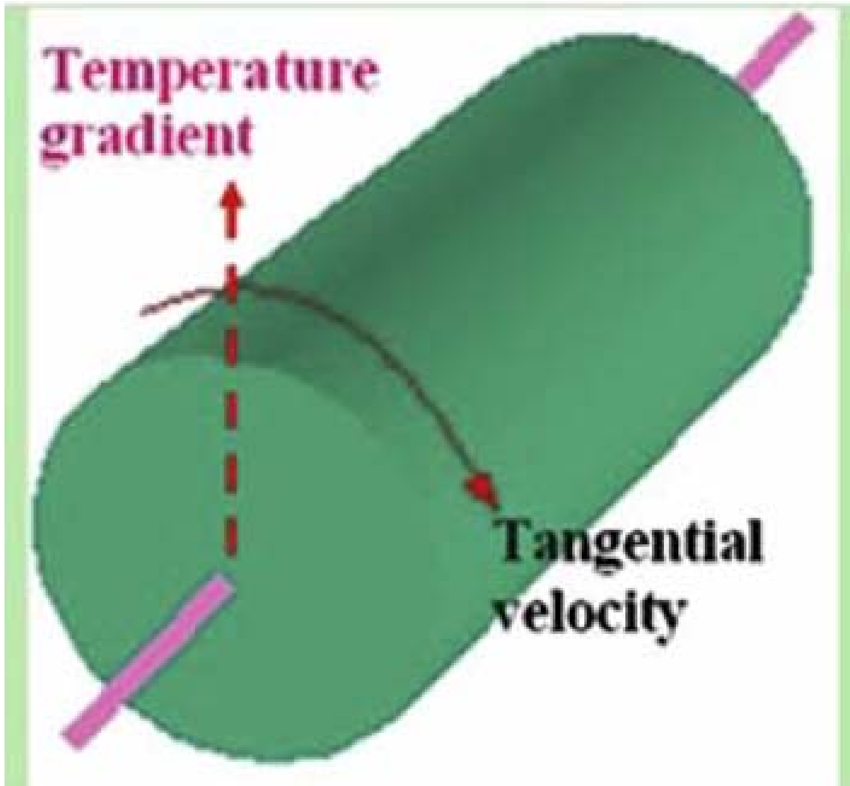
例 2 说明


y
$T_{f,out}$
$T_{s,r}$
L
0
$T_{f,in}$
U_0

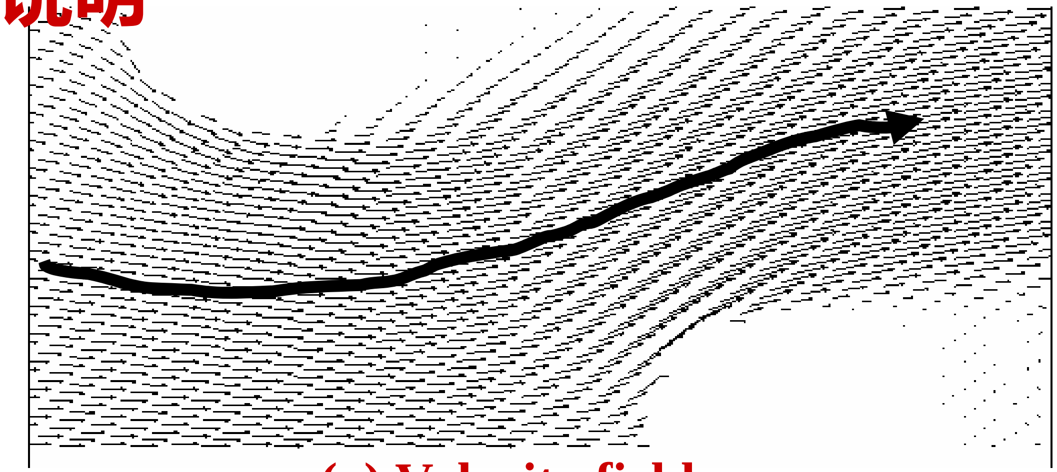

(b)
rice particle
dp=2.736mm
L=20mm
rotating speed
n=400rpm
n=500rpm
n=600rpm
Nu_p
Pe
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
20 40 60 80 100 120 140 160 180 200 220 240

例 3 说明

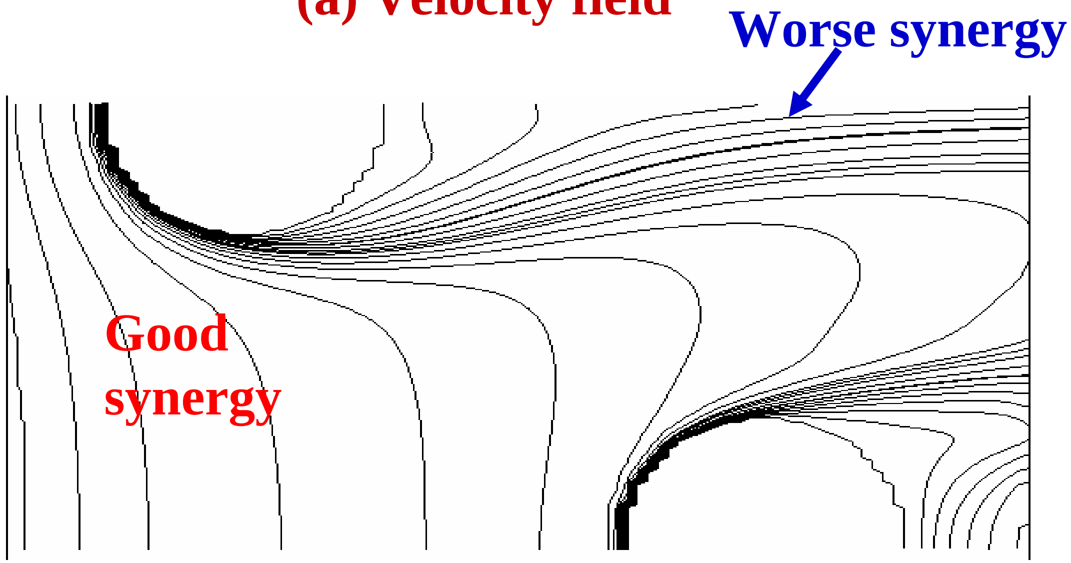

(a)
Outline of the patent
(b)


Temperature gradient
Tangential velocity

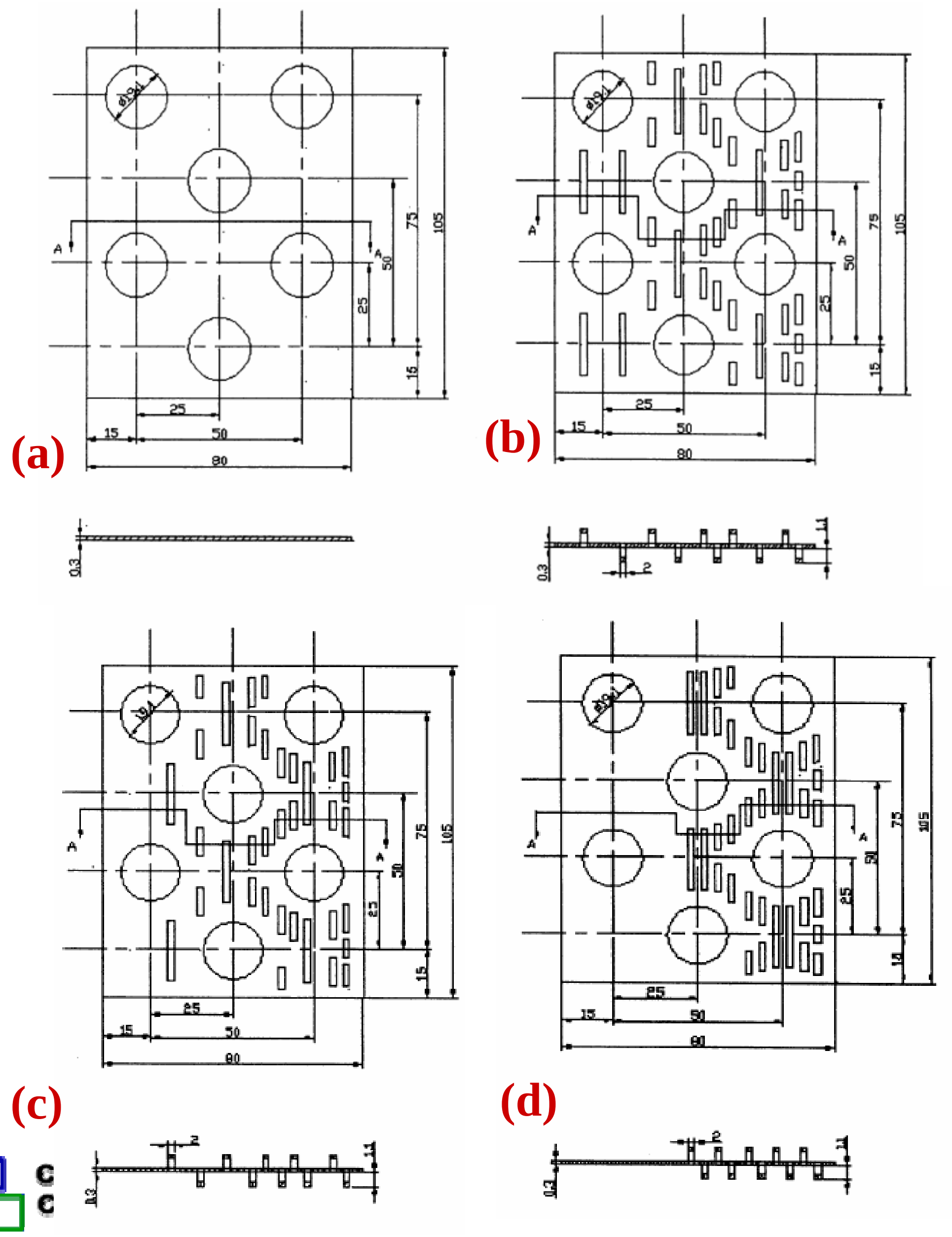
例 L1 说明



(a) Velocity field



(b) Isothermals



(a) (b) (c) (d)

Plain plate fin and three versions of slotted fin designed with the front sparse and rear dense rule

(a) Plain plate

(b) Version 1

(c) Version 2

(d) Version 3

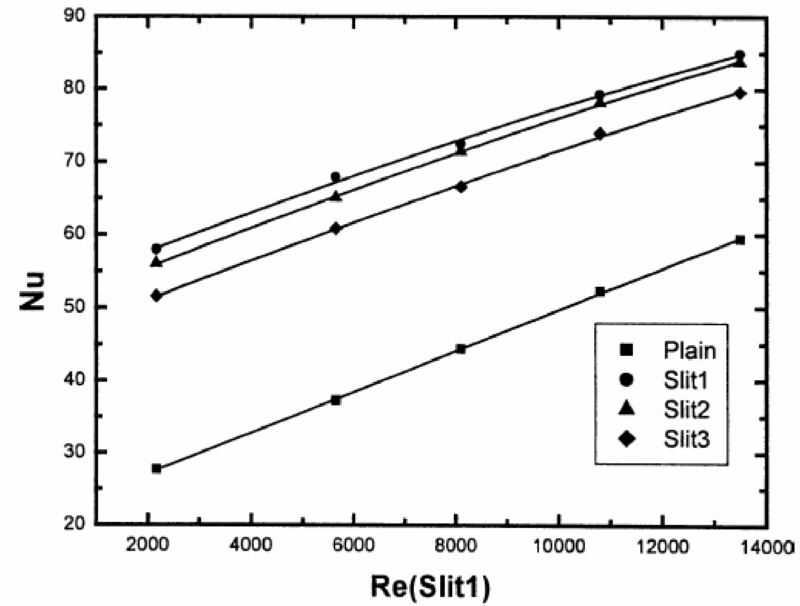


Fig. Predicted Nusselt number of four types of fin

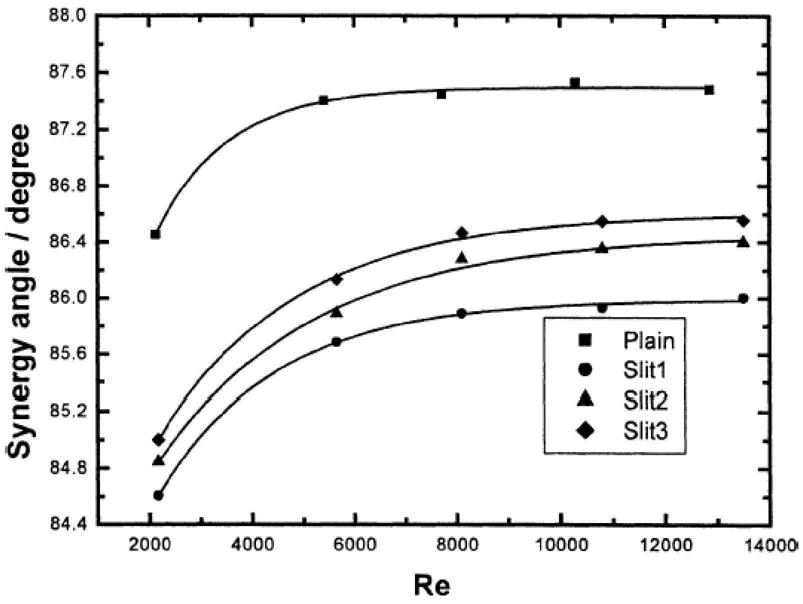
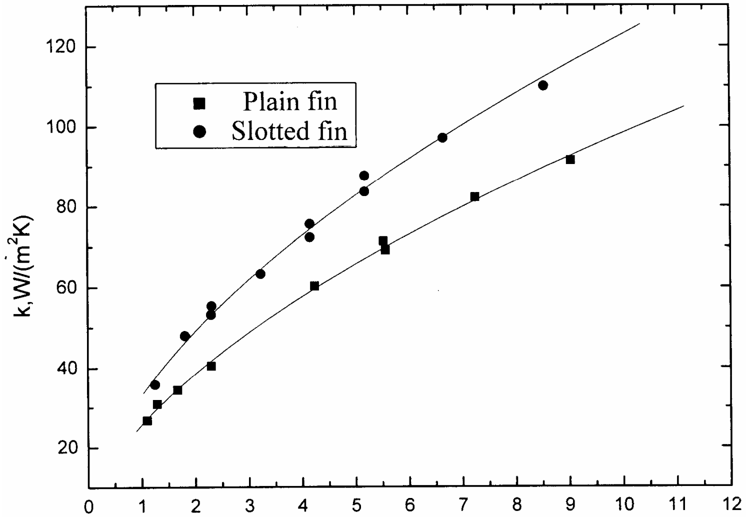


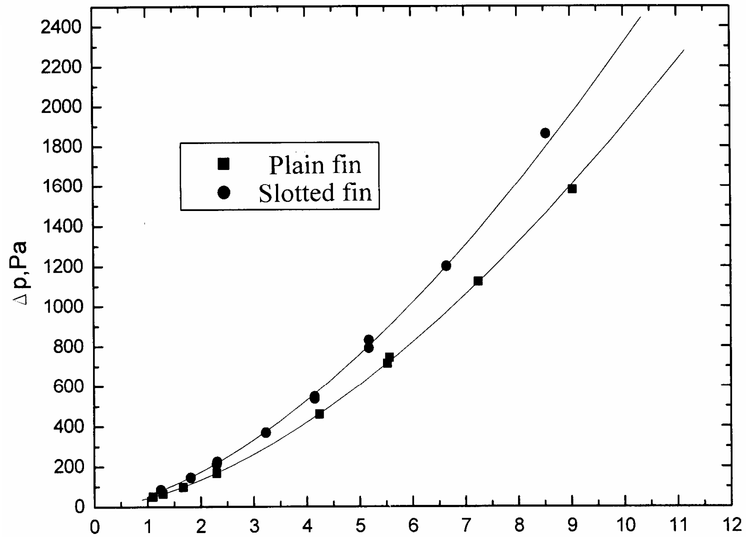
Fig. Synergy angle vs Re for the four types of fins

例 L1 说明



Minimum enhancement in k is 26%

(a) Overall heat transfer coefficient



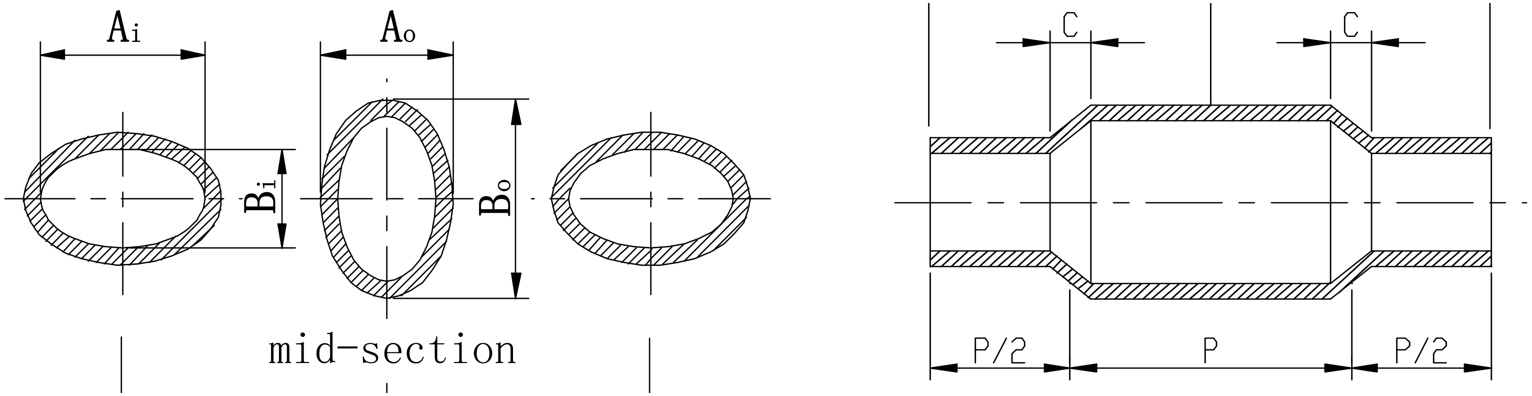
Maximum increase in f is 22%

(b) Air side pressure drop

Test results for the selected slotted fin surface

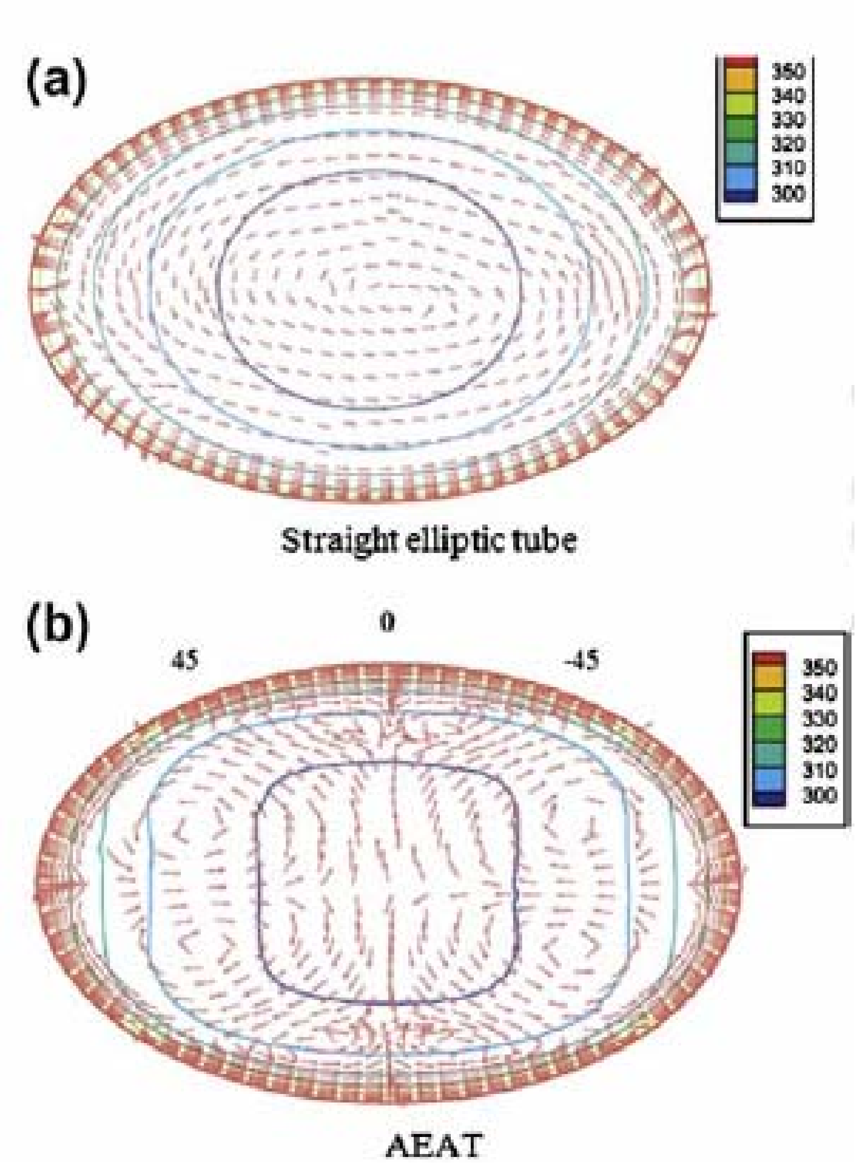
例 L 说明

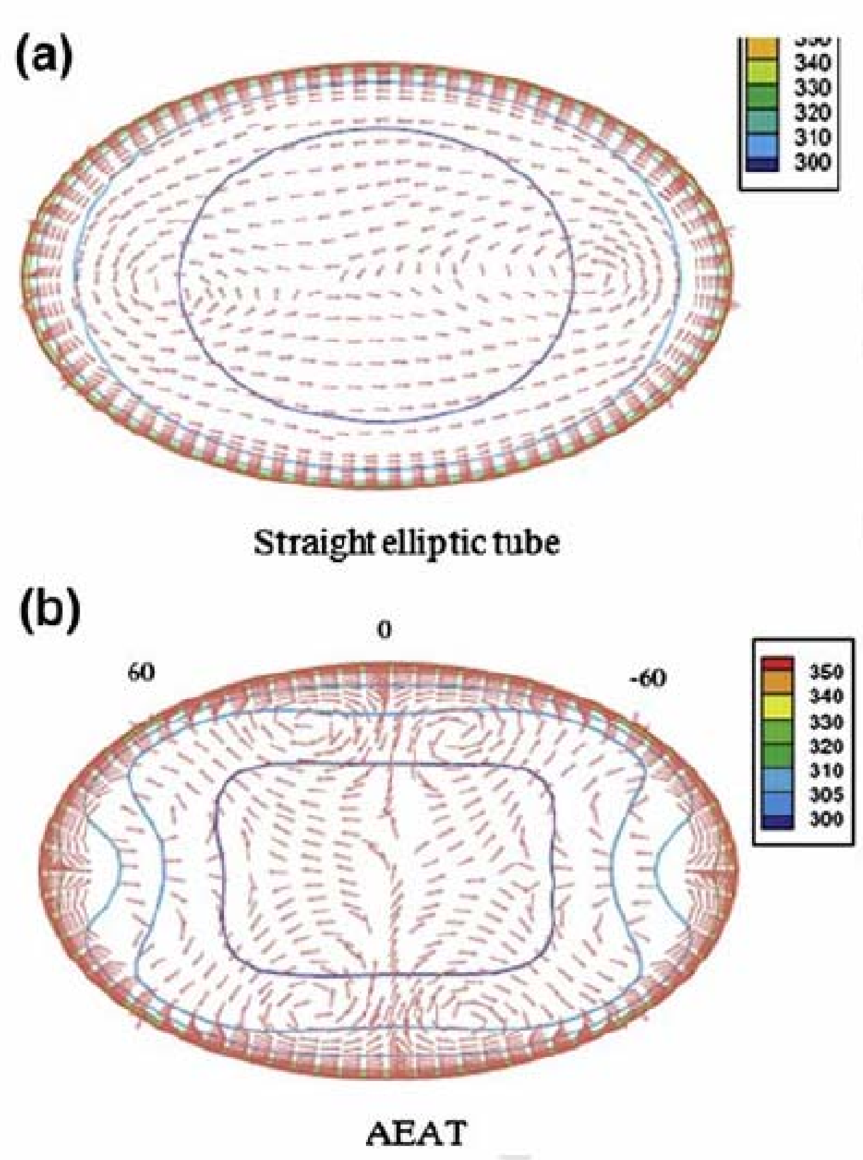
(a) Picture of AEAT



(b) Cross section views

Alternating elliptical axis tubes





Re=2000 **Re=20000**

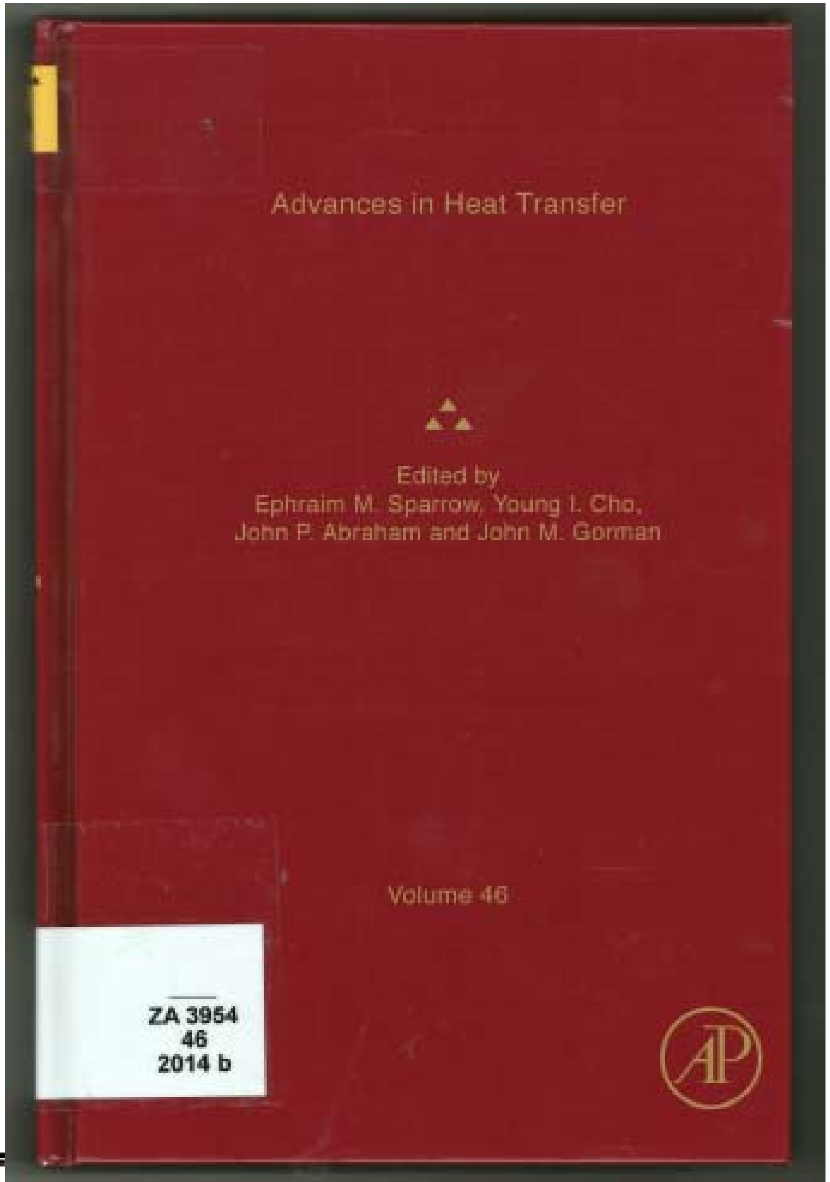
4. 4 场协同原理提出后学界的评价

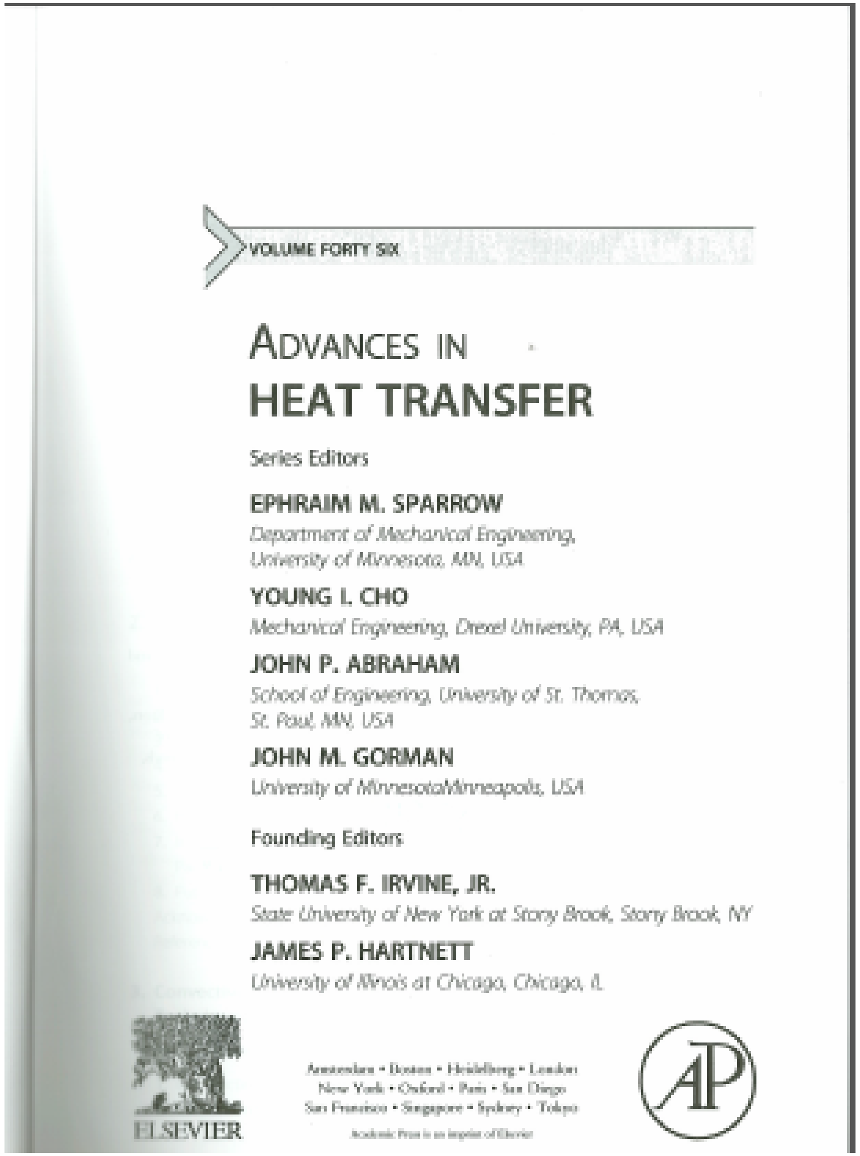
4.4.1 A.E.Bergles 的评价（124）：

He wrote: ‘In addition to keeping an eye out for new literature, it is recommended that the practitioner of enhanced heat transfer consider two more fundamental and philosophical works that appeared recently. Guo [33] advanced the Field Coordination Principle, which states that the coordination between the fluid velocity and the temperature gradient determines the convective heat transfer enhancement.”

（124） A.E. Bergles .Recent developments in enhanced heat transfer. Heat Mass Transfer, 47(2011) 1001–1008

4.4.2 何雅玲、陶文铨的评价（125）：





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Convective Heat Transfer Enhancement: Mechanisms, Techniques, and Performance Evaluation

Ya-Ling He and Wen-Quan Tao[1]
Key Laboratory of Thermo-Fluid Science & Engineering, School of Energy & Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China
[1]Corresponding author: E-mail: wqtao@mail.xjtu.edu.cn

Contents

Advances in Heat Transfer, Volume 46
ISSN: 0065-2717

CFD-NHT-EHT CENTER

1.The basic mechanism of enhancing single phase convective heat transfer, whether laminar or turbulent, transient or stead, elliptic or parabolic, is to make a better synergy between velocity and fluid temperature gradient, i.e., to reduce the synergy angle between velocity and temperature gradient. All the existing explanations for enhancing single phase convective heat transfer can be unified by the FSP.

In our understanding this means that the FSP is not just a method to explain some enhanced techniques, but will have some important impact on the convective heat transfer theory. To the authors' knowledge, the major contributions of the FSP can be summarized into following three aspects.

（1）FSP revealing the condition for velocity to play a role in convective heat transfer

（2）FSP revealing the upper limit of exponent m in correlation of

$$Nu \sim \mathrm{Re}^m$$

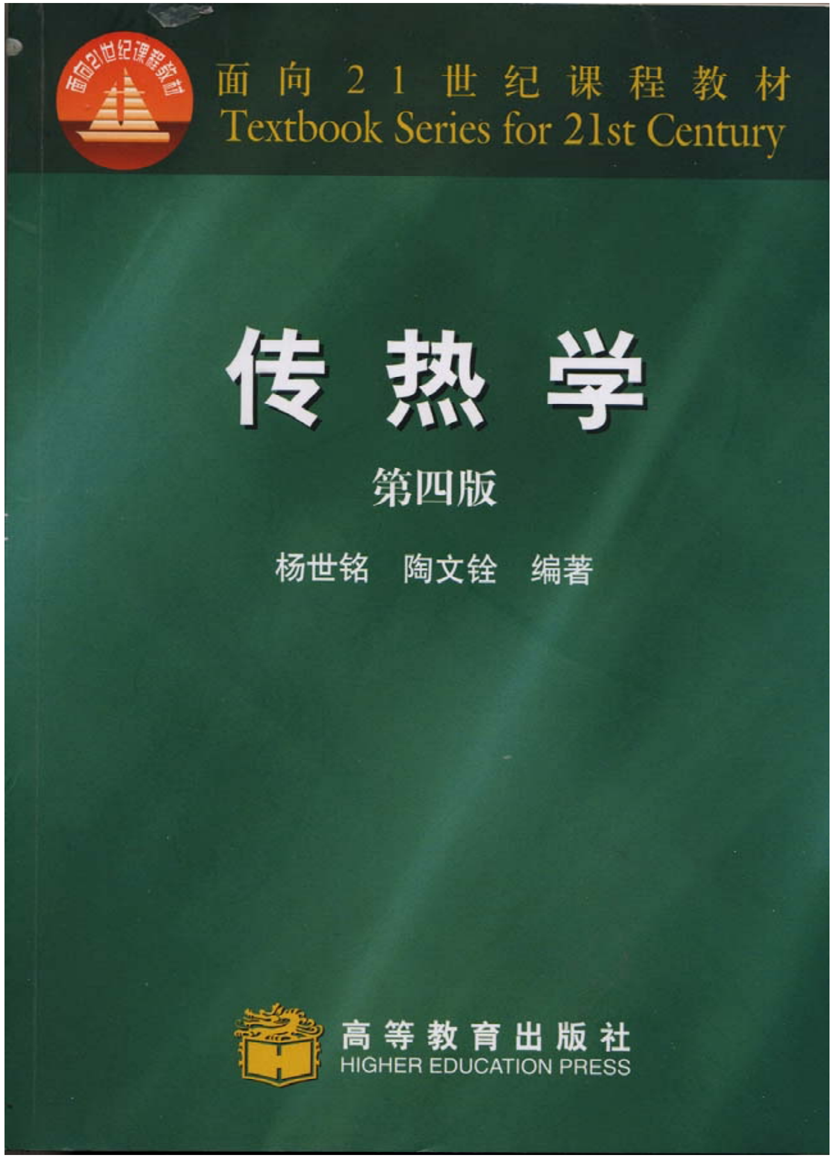
（3）FSP explaining fundamental reasons of characteris-Tics for some basic and enhanced heat transfer cases

These include: why the fully developed Nusselt number of a circle tube of uniform heat flux is larger than that of uniform wall temperature, why the local heat transfer coefficient of the stagnation point of a jet is so high, and the roles of fins are not only extending the cheat transfer surface but also improving the synergy between velocity and temperature gradient.

4.3.3 Advances in Heat Transfer 现主编Sparrow教授等的评价：

Sparrow教授等四位主编在Advances in Heat Transfer -46 的前言中写道：

A contribution by Wen-Quan Tao and Ya-Ling He proposes a means of enhancing single-phase convective heat transfer. That method, termed the field synergy principle, reduces the intersection angle between the fluid velocity and temperature gradients. Clear guidelines are proposed to accomplish the optimization in practical problem.



杨编《传热学》第四版(2006-08, 高等教育出版社)纳入了这一内容。

10-5 热量传递过程的控制（强化与削弱）

在有热量传递的各个技术过程中，常常需要强化传热过程以节约能源、缩小设备尺寸、减轻重量，或使受热部件得到有效的冷却、保证设备安运行。另一方面也有需要削弱热量传递过程以减少热损失的情形。 这是热量传递过程的控制问题，构成了传热学中两类目标相反的命题：传热的强化和传热的削弱。

按照本书前述各章介绍的热量传递的三种基本方式的影响因素和可以控制的范围，大致可以认为：传热强化的研究主要集中在对流换热与辐射换热，而传递过程的削弱则主要通过导热环节来进行。其中对流换热强化技术的研究尤为活跃，是近半个世纪以来国际传热学界的热门课题。相变换热的强化技术和辐射换热的增强与削弱技术已经分别在节 7-3, 7-6 和 9-5 中介绍过，本节着重讨论强化单相对流换热的技术及机理和通过控制导热来削弱热量传热的问题。

10-5-1 强化传热问题概说

所谓“强化传热”（ 英语称为 heat transfer enhancement, augmentation 或 intensification）是指增加热传递过程的传热量，由传热过程方程式（10-10）或对流传热牛顿冷却公式（5-1）可见，增加传热面积、增加传热温差以及增加传热系数或对流传热系数都可以增加所传递的热量。而所谓“强化传热技术”则是指在一定的传热面积与温差下，

凝结则要减薄所形成的液膜厚度。

10-5-3 强化单相对流传热技术机理的进一步探讨

强化传热技术的研究虽然已经经历了半个世纪，但关于强化传热技术的基本机理的认识却没有一个统一的认识。为简便起见，我们暂时把讨论的范围限在单相对流换热的范围内。前面指出，减薄热边界层和增加流体中的扰动都可以强化换热，现在广泛采用的单相对流强化换热表面也都是按照这样的思路设计的。现在要问：减薄热边界层厚度与增加流体中的扰动之间有什么内在关系，其共同的本质是什么？这个问题直到上世纪末才由我国学者过增元给出了明确的答复[31-33]。

在文献[31] 中，作者将边界层型的对流换热能量方程对热边界层厚度作积分，得

$$\rho c_p \int_0^{\delta_t} (\overline{U} \cdot gradT) = -(\lambda \frac{\partial T}{\partial y})_{y=0} = q_w \qquad (10\text{-}26)$$

其中：q_w 是固体表面上流体与固体之间所交换的热量，即对流换热量。根据矢量的运算 规则，有 $\overline{U} \cdot gradT = |\overline{U}||gradT|\cos\theta$。所以文献[31-33]指出，在一定的速度及温度梯度下，减小两者间的夹角 θ 是强化传热的有效措施。

对于有回流的椭圆型的流动，以图 10-42 所示的流过一个后台阶的对流换热为例，将能量方程对计算区域 abcdea 作积分[34]：

西安交通大学教学进度计划

2013—2014 学年第一学期

课 程 名 称 强化传热技术及应用

适应专业班级 能动 2010 级

任 课 教 师 曾敏，王秋旺，陶文铨

系 主 任

总学时	已完成学时	本学期学时				课外学时	
		合计	讲课	实验	机时	讨论	实验
32	0		32				
学分数		2					

周次	日期	教学环节	内容	课内学时	课外学时	备注
9	11.5	授课	1-1 Introduction 1-2 The Enhancement Techniques 1-3 Benefits of Enhancement *(Dr. Min Zeng)*	2		多媒体
9	11.8	授课	1-4 Commecial Applications of Enhanced Surfaces 1-5 Definition of Heat Transfer Area 1-6 Potential for Enhancement *(Dr. Min Zeng)*	2		多媒体

13	12.06	授课	6-1 Twisted Tape Insert 6-2 Segmented Twisted Tape Insert 6-3 Displaced Enhancement Devices 6-4 Wire Coil Inserts 6-5 Extended Surface Insert *(Dr. Min Zeng)*	2		多媒体
14	12.10	授课	7-1 Internally Finned Tubes 7-2 Spirally Fluted Tubes 7-3 Advanced Internal Fin Geometries *(Dr. Min Zeng)*	2		多媒体
14	12.13	授课	8-1 Techniques Employed for Boiling Enhancement 8-2 Single-Tube Pool Boiling Tests of Enhanced Surfaces 8-3 Boiling Mechanism on Enhanced Surfaces *(Dr. Min Zeng)*	2		多媒体
15	12.17	授课	9-1 Basic Approaches to Enhanced Film Condensation 9-2 Dropwise Condensation 9-3 Survey of Enhancement Methods 9-4 Surface Tension Drained Condensation *(Dr. Min Zeng)*	2		多媒体
15	12.20	授课	10 High efficiency and High Temperature Heat Exchangers *(Prof. Qiuwang Wang)*	2		多媒体
16	12.24	授课	11 Field Synergy Principle and Its Applications *(Prof. Wenquan Tao)*	2		多媒体
16	12.27	授课	Summary *(Dr. Min Zeng)*	2		多媒体

目　录

1. 热线概念的最主要功能是显示二维物体中热能传递的路径，即传热过程的可视化（**visualization**）；**就作者所知没有一篇应用热线的文章阐述过如何利用热线概念来强化传热过程**；而场协同的根本作用是揭示了强化单相对流传热的基本机制是改善流体速度与流体温度梯度的协同性，场协同原理不具备显示热能传递路径的功能，就作者所知，**也从来没有一篇关于场协同原理的文章声称过场协同原理具有这个功能；**

2. 热线（**Heatline-1983)**和场协同（**Synergy-1998)**都是对于对流换热理论和认识的发展；获得热线需要求解一个泊桑方程；研究协同需要获得速度与温度梯度的夹角；**他们理论内容的本身是各自独立的，任何一种无法导出另一种，也无法从另一种被导出；**

3.热线可以作为数值计算后处理的技术而纳入商业软件，以清楚显示二维对流换热问题热量传递的路径；但受到热线定义本身固有的限制，这个概念只能应用与二维问题；而场协同则不受此限；

4.从现有应用结果看热线问题绝大部分限于各种自然对流及简单的强制对流，尚未见到更加复杂情况的分析；而场协同原理已经应用于多种复杂对流问题的强化，而且获得了实际的效果；

5.从数值计算角度为了获得热线需要求解热线所满足的泊桑方程，显著增加计算工作量，因此有学者提出了不需要求解泊桑方程同样可以显示热能传递方向的能量矢量的方法；无论是场协同数的计算还是协同角的计算都不需要求解附加的微分方程，很容易从流场及温度场的模拟结果获得所需的信息。

致 谢

本报告准备过程中陈磊博士在提供参考文献方面给予了十分及时的帮助与支持，特此致谢！

陶文铨、何雅玲所指导的多位研究生从实验及数值模拟方面作出了重要贡献，特此致谢！

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Thanks for your attention!

同舟共济

渡彼岸!

People in the same boat help each other to cross to the other bank, where....