Numerical Heat Transfer

Chapter 3 Numerical Methods for Solving Diffusion Equation and their Applications (2)

(Chapter 4 of Textbook)

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Contents

3.4 TDMA & ADI Methods for Solving Algebraic Equations

3.4.1 TDMA algorithm (算法) for 1-D conduction problem

1.General form of algebraic equations of 1-D conduction problems

2.Thomas algorithm

3.Treatment of 1^{st} kind boundary condition

3.4.2 ADI method for solving multidimensional problem

1. Introduction to the matrix of 2-D problem

2. ADI iteration of Peaceman-Rachford

3.4 TDMA & ADI Methods for Solving ABEqs

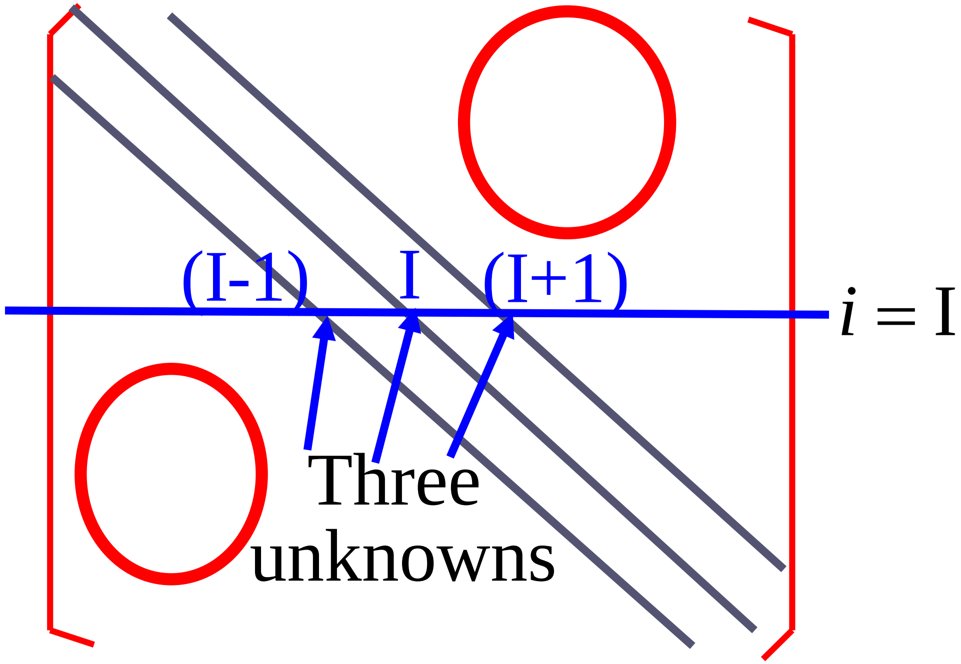
3.4.1 TDMA algorithm for 1-D conduction problem

1.General form of algebraic equations. of 1-D conduction problems

The ABEqs for steady and unsteady (f >0) problems take the following form

$$a_1T_1 + a_2T_2 + ... + a_iT_i + ... + a_{M1}T_{M1} = b \ (i = 1, M1)$$

$$a_P T_P = a_E T_E + a_W T_W + b$$



The matrix (矩阵) of the coefficients is a tri-diagonal (三对角) one .

2. Thomas algorithm(算法)

The numbering method of W-P-E is humanized (人性化), but it can not be accepted by a computer!

Rewrite above equation：

$$A_i T_i = B_i T_{i+1} + C_i T_{i-1} + D_i,\ i = 1, 2, \ldots..M1 \quad \textbf{(a)}$$

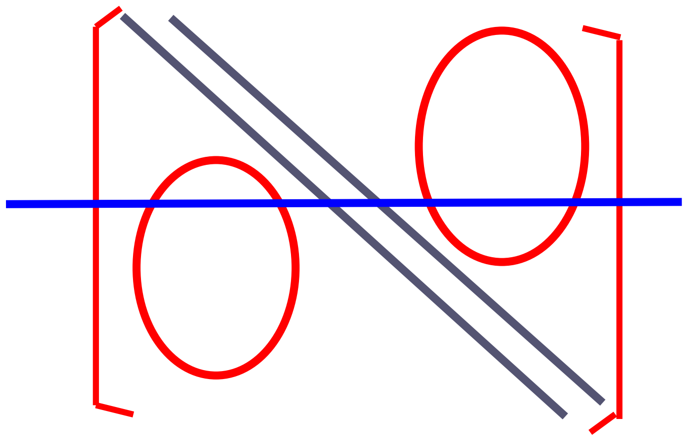
End conditions： i=1, C_i=C_1=0; i＝$M1$, B_i=B_{M1}=0

(1) Elimination (消元)－Reducing the unknowns at each line from 3 to 2

Assuming the eq. after elimination as

$$T_{i-1} = P_{i-1} T_i + Q_{i-1} \quad \textbf{(b)}$$

Coefficient has been treated to 1.



The purpose of the elimination procedure is to find the relationships between P_i, Q_i with A_i, B_i, C_i, D_i:

Multiplying Eq.(b) by C_i, and adding to Eq.(a):

$$A_i T_i = B_i T_{i+1} + \cancel{C_i T_{i-1}} + D_i \qquad \textbf{(a)}$$

$$\cancel{C_i T_{i-1}} = C_i P_{i-1} T_i + C_i Q_{i-1} \qquad \textbf{(b)}$$

$$A_i T_i - C_i P_{i-1} T_i = B_i T_{i+1} + D_i + C_i Q_{i-1}$$

Yielding $$T_i = \left(\frac{B_i}{A_i - C_i P_{i-1}}\right) T_{i+1} + \frac{D_i + C_i Q_{i-1}}{A_i - C_i P_{i-1}}$$

Comparing with $$T_{i-1} = P_{i-1} T_i + Q_{i-1}$$

$$P_i = \frac{B_i}{A_i - C_i P_{i-1}}; \qquad Q_i = \frac{D_i + C_i Q_{i-1}}{A_i - C_i P_{i-1}};$$

The above equations are recursive (递归的)－i.e.,

In order to get P_i, Q_i, P_1 and Q_1 must be known.

In order to get P_1, Q_1, use Eq.(a)

$$A_i T_i = B_i T_{i+1} + C_i T_{i-1} + D_i,\ i = 1, 2, \ldots . M1 \quad \text{(a)}$$

and the left end condition: ***i*=1, *C*$_i$=0**

Applying Eq.(a) to $i=1$, and comparing it with Eq.(b)

$$T_{i-1} = P_{i-1} T_i + Q_{i-1}$$

the expressions of P_1, Q_1 can be obtained:

From $i=1, C_1=0$, Eq.(a) becomes: $A_1T_1 = B_1T_2 + D_1$

$$T_1 = \frac{B_1}{A_1}T_2 + \frac{D_1}{A_1} \longrightarrow P_1 = \frac{B_1}{A_1}; \quad Q_1 = \frac{D_1}{A_1}$$

(2) Back substitution(回代) －Starting from M1 via Eq.(b) to get T_i sequentially（顺序地）

$$T_{M1} = P_{M1}T_{M1+1} + Q_{M1}, \quad P_i = \frac{B_i}{A_i - C_iP_{i-1}};$$

End condition：
i＝$M1$, B_i＝0 $\longrightarrow$ $P_{M1} = 0$

$T_{M1} = Q_{M1}$ $\boxed{T_{i-1} = P_{i-1}T_i + Q_{i-1}}$ to get: $T_{M1-1}, \ldots\ldots T_2, T_1$.

3. Implementation of Thomas algorithm for 1st kind B.C.

For 1st kind B.C., the solution region is from i=2...to M1-1=M2, because T_1 and T_{M1} are known.

Applying Eq.(b) to i =1 with given $T_{1,given}$:

$$T_1 = P_1 T_2 + Q_1 \longrightarrow P_1 = 0\,;\ \ Q_1 = T_{1,given}$$

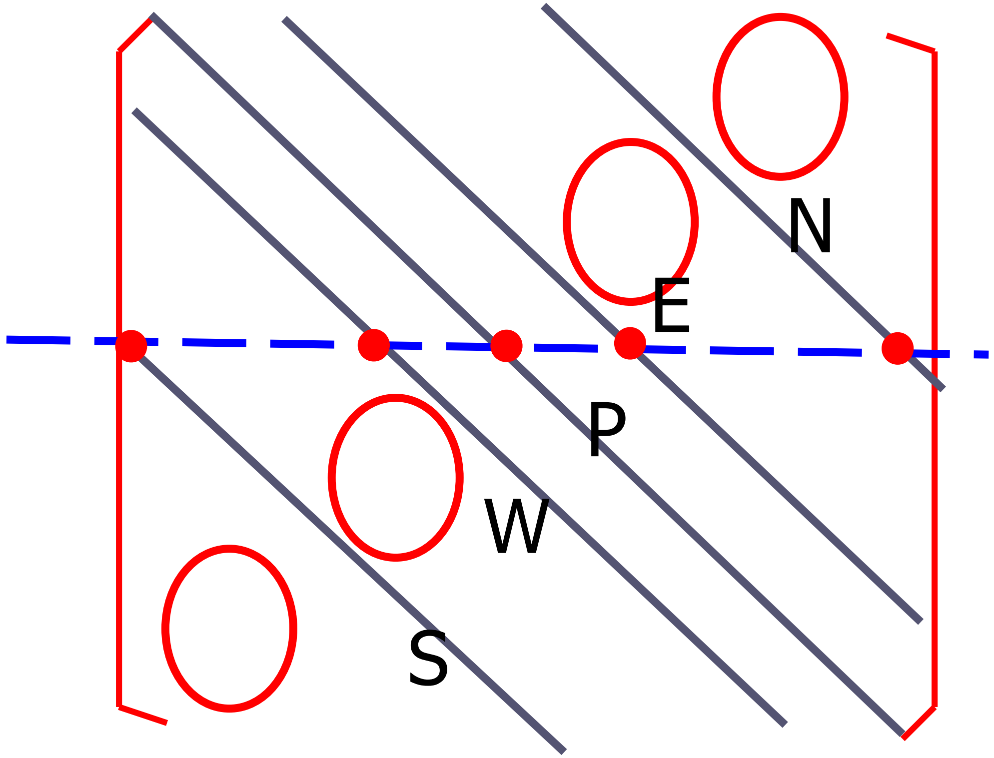
Because T_{M1} is known， back substitution should be started from M_2:

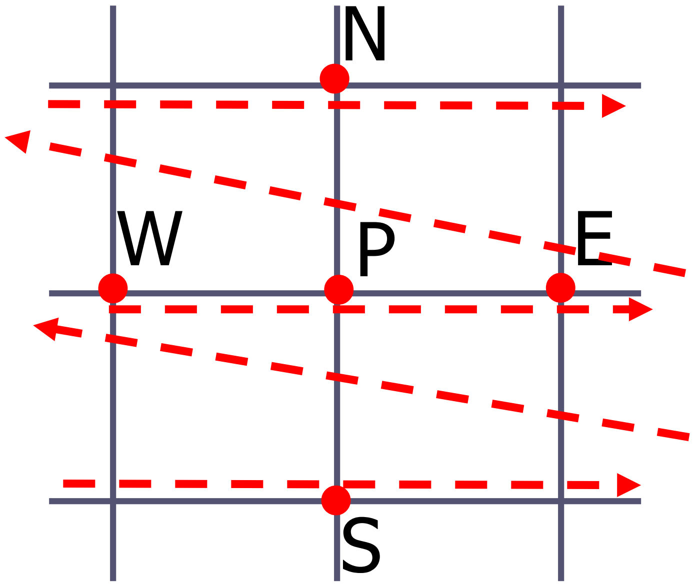
$$T_{M2} = P_{M2} T_{M1} + Q_2$$

When the ASTM is adopted to deal with B.C. of the 2nd and 3rd kind, the numerical B.C. for all cases is regarded as 1st kind, and the above treatment should be adopted.

3.4.2 ADI method for solving multi-dimensional problem

1. Introduction to the matrix of 2-D problem





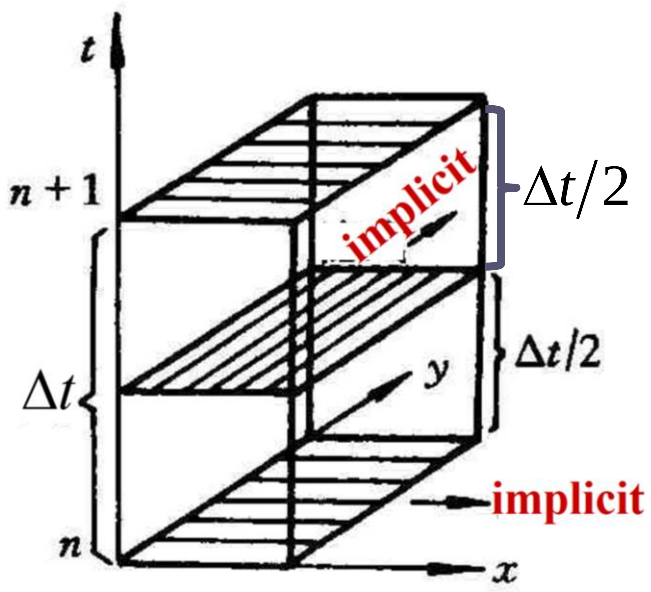
1-D storage (一维存储) of variables and its relation to matrix coefficients

Numerical methods for solving ABEqs. of 2-D problems.

(1) Penta-diagonal algorithm(PDMA,五对角阵算法)

(2) Alternative (交替的)-direction implicit (ADI, 交替方向隐式方法)

2. 2-D Peaceman-Rachford ADI method



Dividing Δt into two uniform parts;

In the 1st $\Delta t / 2$ implicit in x direction, and explicit in y direction;

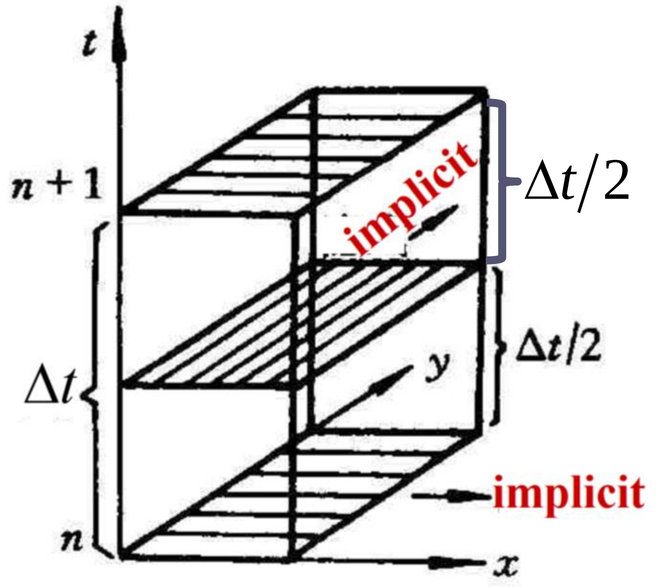
In the 2nd $\Delta t / 2$ implicit in y direction, and explicit in x direction.

Set $u_{i,j}$ the temporary(临时的) solutions at the first sub-time levels

$\delta_x^2 T_{i,j}^n$ ---CD scheme for 2nd derivative at n time level in x direction

$$\delta_x^2 T_{i,j}^n = \frac{T_{i+1,j}^n - 2T_{i,j}^n + T_{i-1,j}^n}{\Delta x^2}$$

2-D ADI



1st sub-time level: $$\frac{u_{i,j} - T_{i,j}^n}{\Delta t / 2} = a(\delta_x^2 u_{i,j} + \delta_y^2 T_{i,j}^n)$$

The solution of $u_{i,j}$ can be obtained by TDMA by taking $\delta_y^2 T_{i,j}^n$ as b-term with known values at n time level

2nd sub-time level: $$\frac{T_{i,j}^{n+1} - u_{i,j}^n}{\Delta t / 2} = a(\delta_x^2 u_{i,j} + \delta_y^2 T_{i,j}^{n+1})$$

$T_{i,j}^{n+1}$ is solved by TDMA and is the solution at time level of (n+1).

3. 3-D Peaceman-Rachford ADI method

Dividing Δt into three uniform parts; In the 1st $\Delta t/3$ implicit in x, and explicit in y, z directions; In the 2nd and 3rd $\Delta t/3$ implicit in y, z direction, and explicit in x, z directions and x,y , respectively;

Set $u_{i,j,k}$, $v_{i,j,k}$ the temporary(临时的) solutions at two sub-time levels

1st sub-time level: $$\frac{u_{i,j,k}-T_{i,j,k}^{n}}{\Delta t/3}=a(\delta_x^2 u_{i,j,k}+\delta_y^2 T_{i,j,k}^{n}+\delta_z^2 T_{i,j,k}^{n})$$

2nd sub-time level: $$\frac{v_{i,j,k}-u_{i,j,k}^{n}}{\Delta t/3}=a(\delta_x^2 u_{i,j,k}+\delta_y^2 v_{i,j,k}+\delta_z^2 u_{i,j,k})$$

3rd sub-time level: $$\frac{T_{i,j,k}^{n+1}-v_{i,j,k}^{n}}{\Delta t/3}=a(\delta_x^2 v_{i,j,k}+\delta_y^2 v_{i,j,k}^{n}+\delta_z^2 T_{i,j,k}^{n+1})$$

The algebraic equations of 3D transient HC problem is updated for one time step by such ADI method: adopting TDMA three times in x,y,z direction respectively.

It's obvious that this solution procedure is not fully implicit, and for 3D case the time step is limited by following stability condition:

$$\boxed{a\Delta t\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}\right)\le 1.5}$$

If the time step is larger than the value specified by the above eq., the resulted numerical solutions will be oscillating (振荡) . We call that the solution procedure is not stable .

More discussion on the numerical stability will be presented in Chapter 7.

Major numerical methods (concepts) introduced in this chapter

1. Fully implicit scheme (全隐格式） of transient problem, which can guarantee （保证） stable and physically meaningful numerical solution;

2.Harmonic mean （调和平均） for determination of interface conductivity;

3.Unified coefficient expression by introducing a scaling factor and a nominal radius;

$$\frac{(\delta x)_e}{\lambda_e} = \frac{(\delta x)_{e^+}}{\lambda_E} + \frac{(\delta x)_{e^-}}{\lambda_P}$$

4.Linearlization of source term（源项线性化） by $S = S_C + S_P\phi_P$, $S_P \le 0$;

5.Additional source term method (ASTM, 附加源项法) for treating 2nd and 3rd kinds of boundary conditions;

6.TDMA （三对角矩阵算法） for solving algebraic equation;

7.General expression of discretized heat conduction eq.

$$a_P T_P = a_E T_E + a_W T_W + b = \sum a_{nb} T_{nb} + b$$

Physical meanings of a_E,a_W:

Reciprocal of thermal resistance between two points, thermal conductance.

3.5 Fully Developed Heat Transfer(FDHT) in Circular Tubes

3.5 Fully Developed HT in Circular Tubes

3.5.1 Introduction to FDHT in tubes and ducts

1. Simple fully developed heat transfer

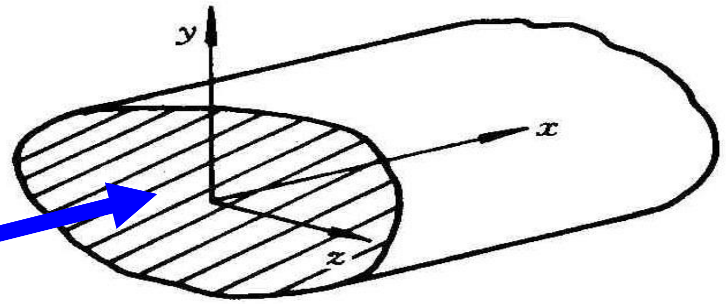
Physically： Velocity components normal to flow direction equal zero; Fluid **dimensionless** temperature distribution is independent on (无关） the position in the flow direction

Mathematically： Both dimensionless momentum and energy equations are of diffusion type.

Present chapter is limited to the simple cases.

FDHT in straight duct is an example of simple cases.

$$\frac{\partial}{\partial x}\left(\frac{T_{w,m}-T}{T_{w,m}-T_b}\right)=0$$

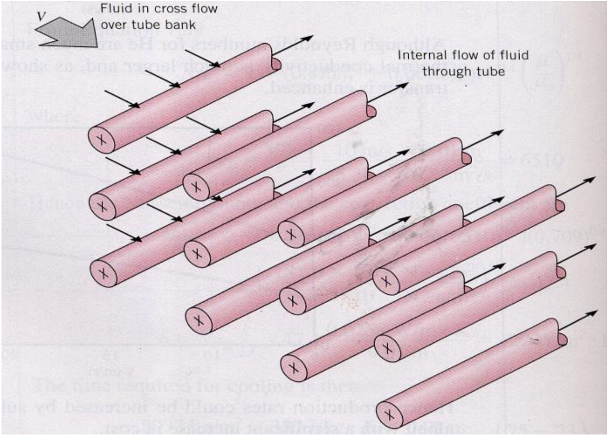


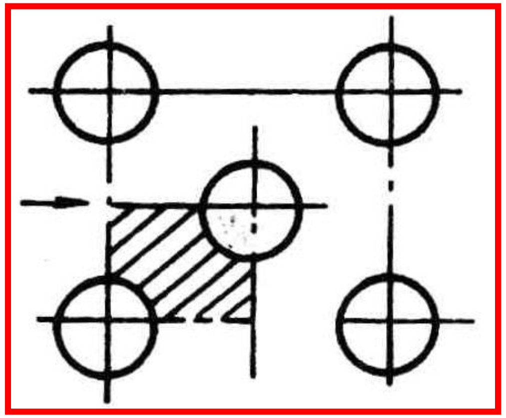
2. Complicated FDHT

In the cross section normal to flow direction there exist velocity components , and the dimensionless temperature depends on the axial position, often exhibits periodic (周期的) character. The full Navier-Stokes equations must be solved .

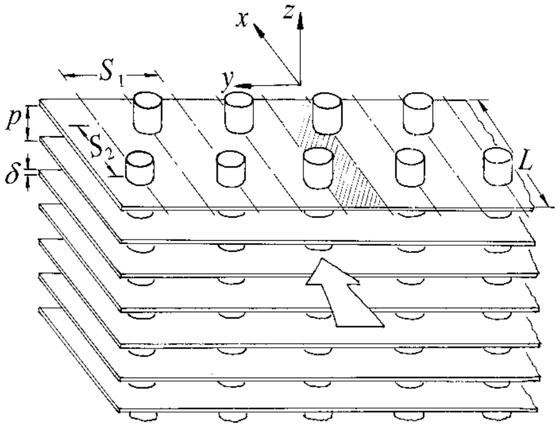
This subject is discussed in Chapter 11 of the textbook.

Examples of complicated FDHT

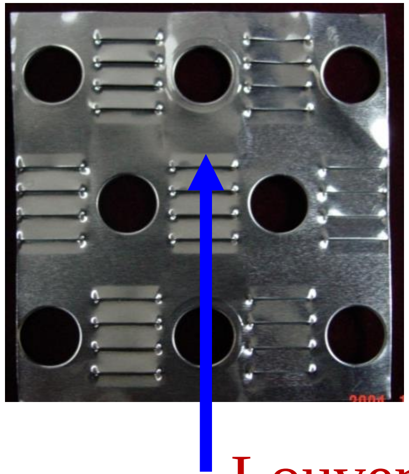


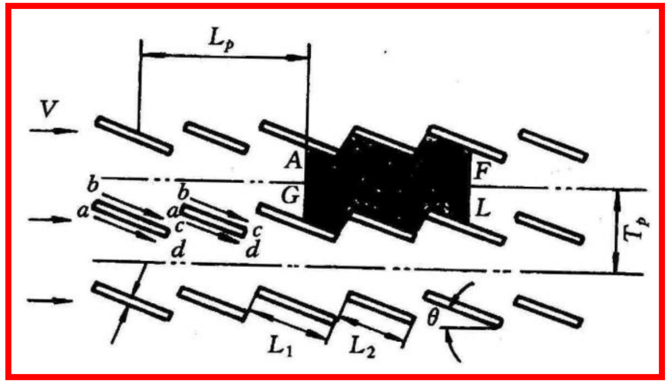


Tube bundle (bank)（管束）



Fin-and-tube heat exchanger

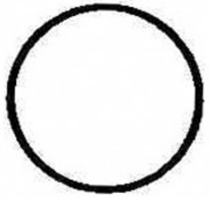




Louver fin (百叶窗翅片)

3. Collection of partial examples

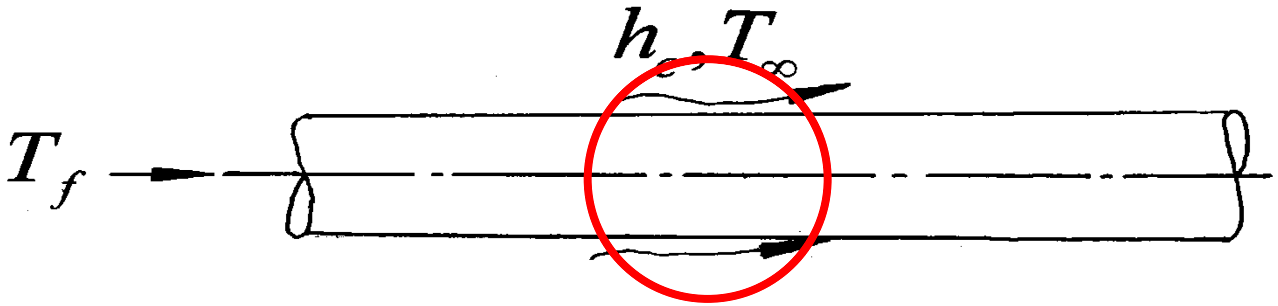
Table 4-5 Numerical examples of simple FDHT

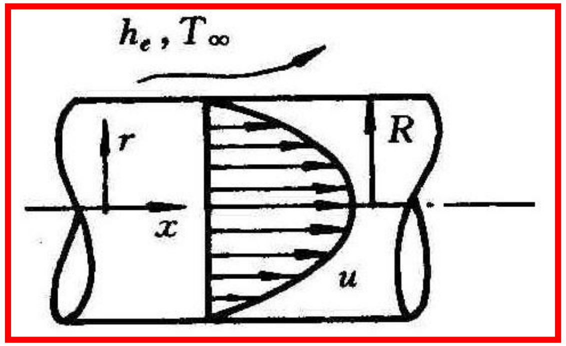
No	Cross section	B. Condition	Refs.
1.		Uniform wall temp.; Uniform periphery wall heat flux; External convective heat transfer, etc.	[23,24, 25,26,27]
2		Uniform wall temp.; Uniform wall heat flux	[23]
3		Uniform wall temp.; Uniform axial wall heat flux Two opposite walls adiabatic and the other two opposite wall uniform temp.	[28,29,30]

See pp. 106-109 of the textbbok for details

3.5.2 Physical and mathematical models of FDHT in circular tube

A laminar flow in a long tube is cooled (heated) by an external fluid with temperature T_∞ and heat transfer coefficient h_e . Determine the in-tube heat transfer coefficient and Nusselt number in the FDHT region.





1. Simplification (简化) assumptions

(1) Thermo-physical properties are constant ;

(2) Axial heat conduction in the fluid is neglected;

(3) Viscous dissipation (耗散)is neglected;

(4) Natural convection is neglected;

(5) Tube wall thermal resistance is neglected;

(6) The flow in tube is steady , laminar and fully developed:

$$\frac{u}{u_m} = 2[1 - (\frac{r}{R})^2]; \qquad v = 0, \; u_m - \text{Mean velocity}$$

2. Mathematical formulation (描述)

(1) Energy equation

Cylindrical coordinate, symmetric temp. distribution, no natural convection (A4) and steady (A6):

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

FD flow (A6)

No axial cond. (A2)

No dissipation (A3)

$$\rho c_p u\frac{\partial T}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)$$

Mathematically, what type is this eq.?

2-D parabolic eq.!

（2） Boundary condition

$$r = 0, \frac{\partial T}{\partial r} = 0$$ （Symmetric condition）；

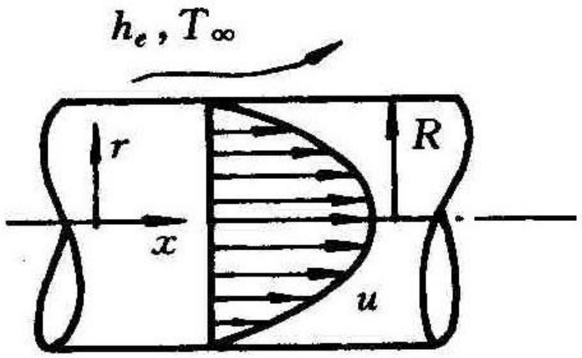
$$\boxed{r = R, -\lambda \frac{\partial T}{\partial r} = h_e (T - T_\infty)}$$

(External convective condition!)

Internal fluid thermal conductivity

External (外部) convective heat transfer coefficient (given)

No wall thermal resistance (A5), equivalent to wall thickness equals zero, tube outer radius ＝tube inner radius=R



3.5.3 Governing eqs. and dimensionless forms

From fully developed condition a dimensionless temperature can be introduced, transforming the PDE to ordinary differential eq..

Given temp.

Cross section average temp.

Defining $$\Theta=\frac{T-T_\infty}{T_b-T_\infty}\leftarrow\frac{T-T}{T_b-T}\leftarrow\frac{T-T}{T-T}$$

Then: $$T=\Theta(T_b-T_\infty)+T_\infty;\quad \frac{\partial T}{\partial x}=\Theta\frac{\partial T_b}{\partial x}=\Theta\frac{dT_b}{dx}$$

Defining two dimensionless spatial coordinates:

$$\eta=\frac{r}{R};\quad X=\frac{x}{R\bullet Pe}\quad Pe=\frac{2R\rho c_p u_m}{\lambda}=\frac{2Ru_m}{a}$$

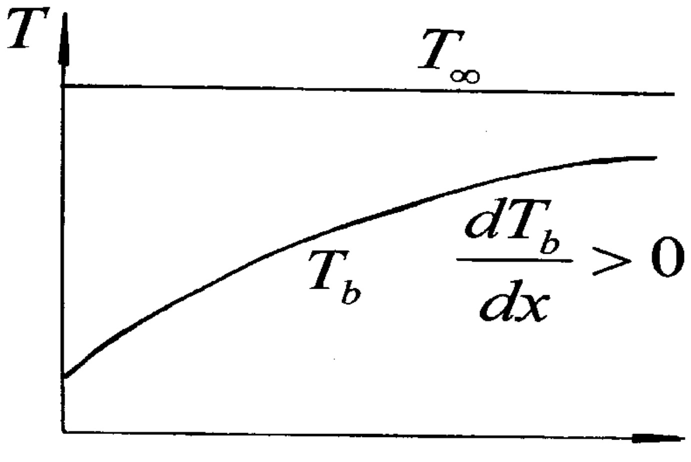
Constant properties（A1）

Thermal diffusivity

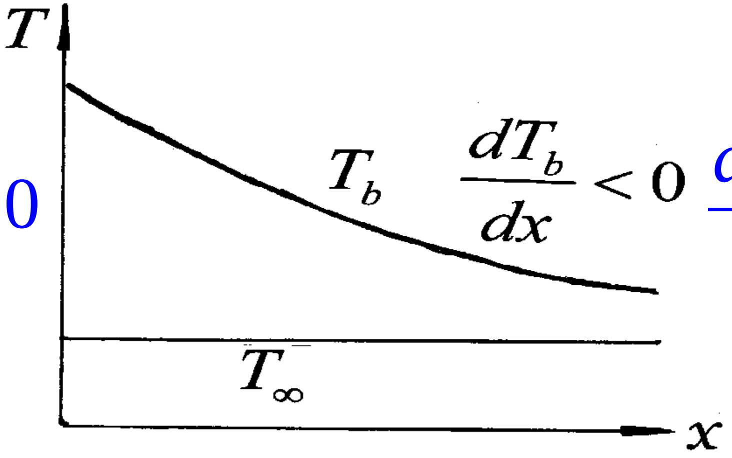
热扩散率

Energy eq. can be rewritten as：

$$\underbrace{\frac{dT_b/dX}{T_b - T_\infty}}_{\text{Dependent on X only}} = \underbrace{\frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\Theta}{d\eta}\right) \Big/ \left(\frac{1}{2}\Theta\frac{u}{u_m}\right)}_{\text{Dependent on } \eta \text{ only}} = -\Lambda \qquad \boxed{\Lambda > 0}$$



$$\frac{dT_b/dX}{T_b - T_\infty} < 0$$



$$\frac{dT_b/dX}{T_b - T_\infty} < 0$$

Λ is called eigenvalue (特征值)

Following ordinary differential equation for the dimensionless temperature can be obtained

$$\frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\Theta}{d\eta}\right)\Big/\left(\frac{1}{2}\Theta\frac{u}{u_m}\right)=-\Lambda \qquad \text{(a)}$$

The inner B.C is transformed (转换成) into: $\eta=0,\ \dfrac{d\Theta}{d\eta}=0$ (b)

The outer B.C $r=R,\ -\lambda\dfrac{\partial T}{\partial r}=h_e(T-T_\infty)$ is transformed into:

$$\eta=1,\ -\frac{d\left(\dfrac{T-T_\infty}{T_b-T_\infty}\right)}{d\left(\dfrac{r}{R}\right)}=\left(\frac{h_eR}{\lambda}\right)\frac{T-T_\infty}{T_b-T_\infty} \rightarrow \left.\frac{d\Theta}{d\eta}\right)_{\eta=1}=-Bi\Theta_w \qquad \text{(c)}$$

Question: whether from Eqs. (a)-(c) a unique (唯一的) solution can be obtained?

3.5.4 Analysis of condition for unique solution

Because of the homogeneous (齐次性) character ：

Every term in the differential equation contains a linear part of dependent variable or its 1st/2nd derivative.

$$\frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\Theta}{d\eta}\right)/\left(\frac{1}{2}\Theta\frac{u}{u_m}\right)=-\Lambda \longrightarrow \frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\Theta}{d\eta}\right)=-\Lambda\left(\frac{1}{2}\Theta\frac{u}{u_m}\right)$$

In addition, the given B.Cs. are also homogeneous:

$$\eta=0,\ \frac{d\Theta}{d\eta}=0; \qquad \frac{d\Theta}{d\eta})_{\eta=1}=-Bi\Theta_w$$

For the above mathematical formulation there exists an uncertainty （不确定性） of being able to be multiplied by a constant for its solution.

While in order to solve the problem, the value of Λ in the formulation has to be determined.

In order to get a unique solution and to specify the eigenvalue, we need to supply one more condition!

We examine the definition of dimenionless temperature:

$$\Theta_b = \left(\frac{T - T_\infty}{T_b - T_\infty}\right)_b = \frac{T_b - T_\infty}{T_b - T_\infty} \equiv 1.0$$

Physically, the averaged temperature is defined by

$$\Theta_b = \frac{\int_0^R 2\pi r u \Theta dr}{\pi R^2 u_m} = 2\int_0^1 \frac{r}{R}\frac{u}{u_m}\Theta d\left(\frac{r}{R}\right) = 1$$

Thus the complete formulation is:

$$\left\{\begin{array}{ll} \frac{1}{\eta}\frac{d}{d\eta}(\eta\frac{d\Theta}{d\eta})+\Lambda(\frac{1}{2}\Theta\frac{u}{u_m})=0 & \text{(a)} \\ \eta=0,\ \frac{d\Theta}{d\eta}=0; & \text{(b)} \\ \frac{d\Theta}{d\eta})_{\eta=1}=-Bi\Theta_w & \text{(c)} \\ \int_0^1 \eta\frac{u}{u_m}\Theta d\eta=1/2 & \text{(d)} \end{array}\right.$$

Non-homogeneous term!

3.5.5 Numerical solution method

$$\rho c_p u \frac{\partial T}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda r \frac{\partial T}{\partial r})$$

Defining $\Theta = \dfrac{T - T_\infty}{T_b - T_\infty}$; $\dfrac{dT_b / dX}{T_b - T_\infty} = \dfrac{1}{\eta}\dfrac{d}{d\eta}(\eta\dfrac{d\Theta}{d\eta}) / (\dfrac{1}{2}\Theta\dfrac{u}{u_m}) = -\Lambda$

$$\frac{1}{\eta}\frac{d}{d\eta}(\eta\frac{d\Theta}{d\eta}) = -\Lambda(\frac{1}{2}\Theta\frac{u}{u_m}) \quad \eta = 0, \frac{d\Theta}{d\eta} = 0; \quad \frac{d\Theta}{d\eta})_{\eta=1} = -Bi\Theta_w$$

$$\Theta_b = (\frac{T_b - T_\infty}{T_b - T_\infty}) \equiv \mathbf{1.0} \Rightarrow \int_0^1 \eta\frac{u}{u_m}\Theta d\eta = 1/2$$

$$\frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\Theta}{d\eta}\right)+\Lambda\left(\frac{1}{2}\Theta\frac{u}{u_m}\right)=0$$

This is a 1-D conduction equation with a source term!

$\frac{\Lambda}{2}\Theta\frac{u}{u_m}$,whose value should be determined during the solution process iteratively (迭代地).

Patankar－Sparrow proposed following numerical solution method:

1） Variable transformation （变量变换）

Let $\Theta=\Lambda\phi$

Because of the homogeneous character, the form of the equation is not changed only replacing Θ by ϕ .

Complete mathematical formulation of the problem

$$\frac{1}{\eta}\frac{d}{d\eta}\left(\eta\frac{d\phi}{d\eta}\right)+\Lambda\left(\frac{1}{2}\phi\frac{u}{u_m}\right)=0 \qquad \text{(a)}$$

$$\eta=0,\ \frac{d\phi}{d\eta}=0; \qquad \text{(b)}$$

$$\left.\frac{d\phi}{d\eta}\right)_{\eta=1}=-Bi\phi_w \qquad \text{(c)}$$

$$\int_0^1 \eta\frac{u}{u_m}\Lambda\phi d\eta=1/2 \qquad \text{(d)}$$

Non-homogeneous equ.

$$\Lambda=1/\left(2\int_0^1 \eta\frac{u}{u_m}\phi d\eta\right)$$

It can be used to iteratively determine the eigenvalue.

2） Solution procedure

(1) Assuming an initial field ϕ^* , to get Λ^*

(2) Solving the algebraic equations of an ordinary differential eq. with a source term to get an improved ϕ

(3) Repeating the above procedure until $\left|(\phi^* - \phi)/\phi\right| \le \varepsilon,$

$$\varepsilon = 10^{-3} \sim 10^{-6}$$

This iterative procedure is easy to approach convergence:

$$S = \Lambda \frac{1}{2}\frac{u}{u_m}\phi = \frac{(u/u_m)\phi}{4\int_0^1 \eta(u/u_m)\phi d\eta} = \frac{(1-\eta^2)\phi}{4\int_0^1 \eta(1-\eta^2)\phi d\eta}$$

ϕ exists in both numerator（分子） and denominator（分母）, thus only the distribution, rather than absolute value will affect the source term.

From converged ϕ

$$\boxed{\Lambda = 1/(2\int_0^1 \eta \frac{u}{u_m}\phi d\eta)}$$

3.5.6 Treatment of numerical results

Two ways for obtaining heat transfer coefficient:

1. From solved temp. distribution using Fourier's law of heat conduction and Newton's law of cooling:

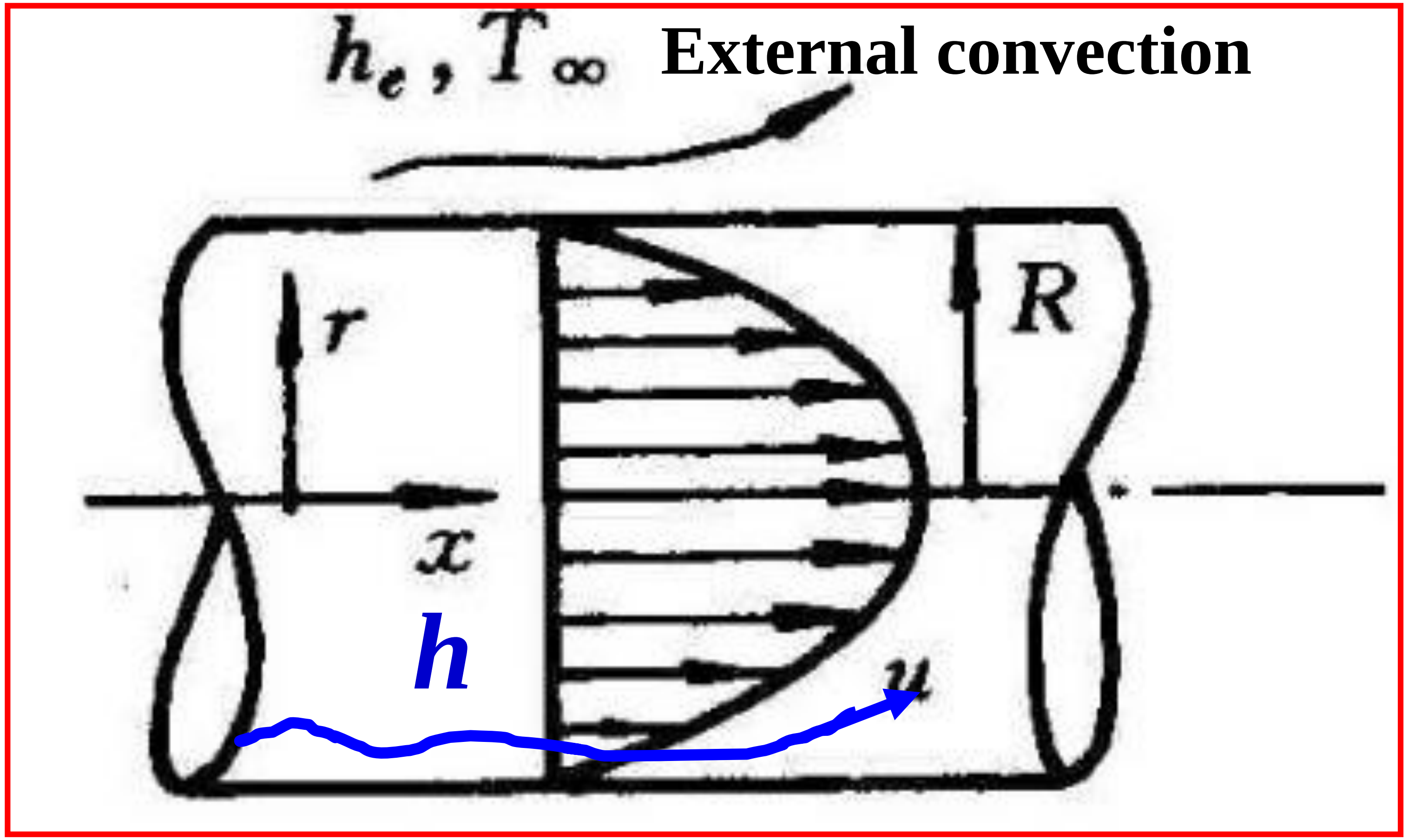
$$r = R, -\lambda \frac{\partial T}{\partial r} = h(T_w - T_b) \rightarrow \boxed{h = -\lambda \frac{\partial T}{\partial r})_{r=R} \frac{1}{T_w - T_b}}$$

For inner fluid

Note: different from boundary condition

$$\boxed{r = R, -\lambda \frac{\partial T}{\partial r} = h_e(T - T_\infty)}$$

$$r = R,\ -\lambda\frac{\partial T}{\partial r} = h(T_w - T_b)$$ (管内流体传热的热平衡条件)



In-tube fluid exchanges heat with tube wall(管内流体与管壁的热交换)

2. From the eigenvalue（特征值）：

From heat balance between inner and external heat transfer

$$h(T_b - T_w) = h_e(T_w - T_\infty)$$

Inner Outer

Get：

$$h = h_e \frac{T_w - T_\infty}{T_b - T_w} \rightarrow h = h_e \frac{1}{\dfrac{T_b - T_w}{T_w - T_\infty}} \rightarrow \frac{h_e}{\dfrac{T_b - T_\infty + T_\infty - T_w}{T_w - T_\infty}}$$

$$\rightarrow \frac{h_e}{\dfrac{T_b - T_\infty}{T_w - T_\infty} - 1} \rightarrow h = \frac{h_e}{\dfrac{1}{\dfrac{T_w - T_\infty}{T_b - T_\infty}} - 1} = \frac{h_e}{\dfrac{1}{\Theta_w} - 1} \rightarrow$$

$$h=\frac{h_e}{\frac{1}{\Theta_w}-1}=\frac{h_e\Theta_w}{1-\Theta_w}=\frac{h_e\Lambda\phi_w}{1-\Lambda\phi_w}$$

$$Nu=\frac{2Rh}{\lambda}=\frac{2R}{\lambda}\frac{h_e\Lambda\phi_w}{1-\Lambda\phi_w}=\frac{2Bi\Lambda\phi_w}{1-\Lambda\phi_w}$$

From the specified values Bi , the corresponding eigenvalues, Λ, can be obtained. Thus it is not necessary to find the 1st-order derivative at the wall of function ϕ for determining Nusselt number.

3.5.7 Discussion on numerical results

Table :Numerical results of FDHT in tubes
In the textbook: Table 4-6

Bi	Λ	Nu
0	0	4.364
0.1	0.381 8	4.330
0.25	0.894 3	4.284
0.5	1.615	4.221
1	2.690	4.122
2	3.995	3.997
5	5.547	3.840
10	6.326	3.758
100	7.195	3.663
∞	7.314	3.657

$(Nu)_q$

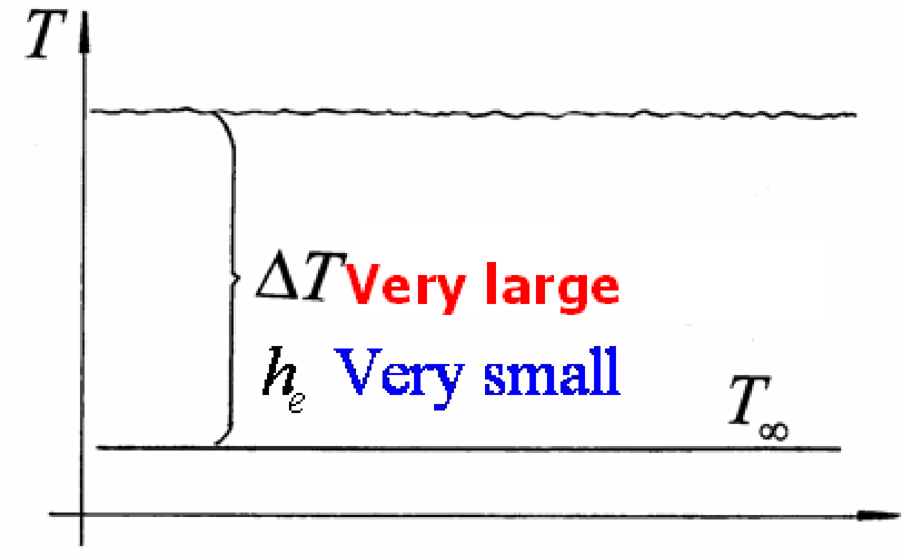
$(Nu)_T$

1. *Bi* effect:

From definition $Bi = \dfrac{Rh_e}{\lambda}$

$Bi \to \infty, \quad h_e \to \infty$ External heat transfer is very strong, the wall temp. approaches fluid temp. This is corresponding to constant wall temp condition, thus $Nu = 3.66$

$Bi \to 0, \; h_e \to 0$ Is this adiabatic? No!



Product of very small HT coefficient and very large temp. difference makes heat flux almost constant.

$$q = h_e \Delta T \approx const$$

2. Computer implementation of $Bi \to \infty$ and $Bi = 0$

$Bi \longrightarrow \infty$ by progressively (**逐渐地**) increasing Bi :

$Bi = 10^5,\ 10^6, 10^7 .....$

$Bi = 0$ by progressively decreasing Bi :

$Bi = 0.1,\ 0.01,\ 0.001,\ 0.0001,\ 0.00001, ...$

Double decision (双精度) data must be used for the computation, because when Bi approaches zero ,both numerator and denominator approach zero:

$$Nu = \frac{2Bi\Lambda\phi_w}{1 - \Lambda\phi_w},\quad Bi \to 0,\ \Lambda \to 0,\ \Lambda\phi_w \to 1 \longrightarrow \frac{\mathbf{0}}{\mathbf{0}}$$

An infinitive!
不定式!

4.6 Fully Developed HT in Rectangle Ducts

4.6.1 Physical and mathematical models

4.6.2 Governing eqs. and their dimensionless forms

4.6.3 Condition for unique solution

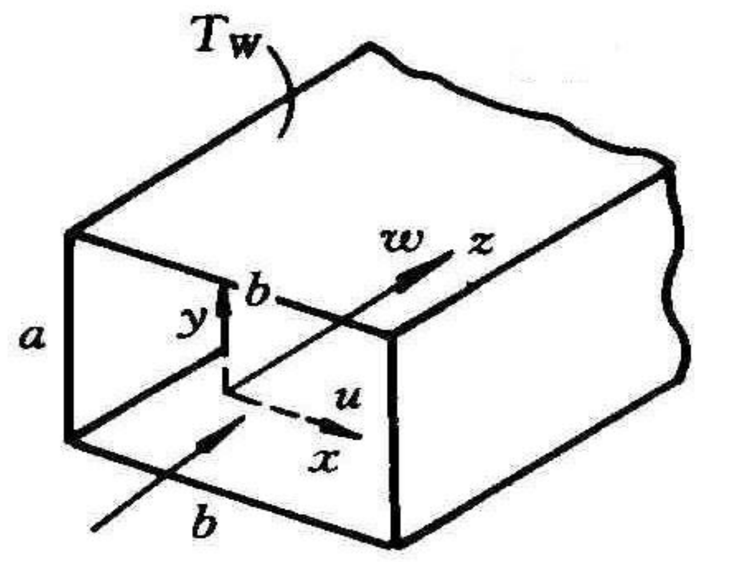
4.6.4 Treatment of numerical results

4.6.5 Other cases

3.6 Fully Developed HT in Rectangle Ducts

3.6.1 Physical and mathematical models

Fluid with constant properties flows in a long rectangle duct with a constant wall temp. Determine the friction factor and HT coefficient in the fully developed region for laminar flow.



1. Momentum equation

For the fully developed flow $u=v=0$, only the velocity component in z-direction is not zero. Its governing equation:

$$\rho(\cancel{u}\frac{\partial w}{\partial x}+\cancel{v}\frac{\partial w}{\partial y}+w\cancel{\frac{\partial w}{\partial z}})=-\frac{\partial p}{\partial z}+\eta(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\cancel{\frac{\partial^2 w}{\partial z^2}})$$

0 0 0 0

$$\eta(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2})-\frac{\partial p}{\partial z}=0$$

Neglecting cross section variation of *p*

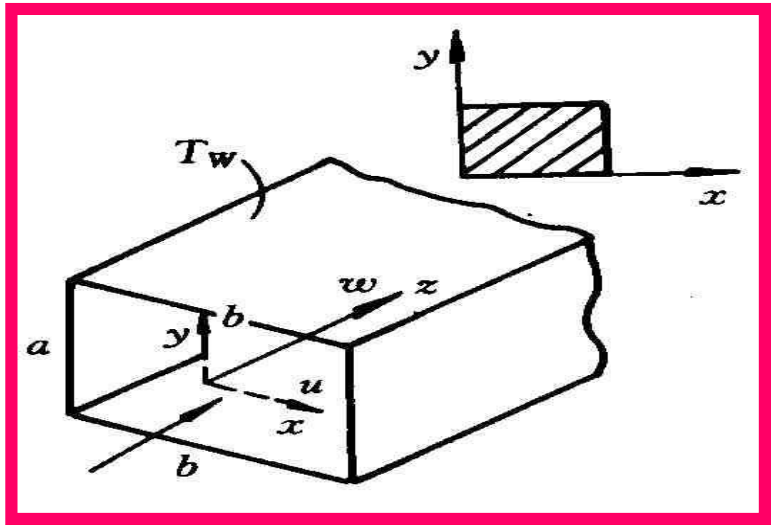
$$\eta(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2})-\frac{dp}{dz}=0$$

This is a 2-D steady heat conduction problem, with a source term .

Taking ¼ region as the computational domain because of symmetry. Boundary conditions are:

At the two walls， $w=0$;

At center line， the first order normal derivative equals zero: $\frac{\partial w}{\partial n}=0$



Defining a dimensionless velocity as：

$$W=\frac{\eta w}{-D^2\dfrac{dp}{dz}}$$

where D is the referenced length, say: $D=a$, or $D=b$.

Defining dimensionless coordinates： $X=x/D$, $Y=y/D$,

then：

$$\eta\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)-\frac{dp}{dz}=0 \rightarrow \begin{cases}\dfrac{\partial^2 W}{\partial X^2}+\dfrac{\partial^2 W}{\partial Y^2}+1=0\\ \text{At two walls,}\quad W=0;\\ \text{At center lines,}\quad \dfrac{\partial W}{\partial n}=0\end{cases}$$

It is a heat conduction problem with a source term of 1 and a constant thermal conductivity!

2. Energy equation

$$\rho c_p\left(\overset{0}{u\frac{\partial T}{\partial x}}+\overset{0}{v\frac{\partial T}{\partial y}}+w\frac{\partial T}{\partial z}\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\overset{0}{\frac{\partial T}{\partial z}}\right)$$

Thus: $$\rho c_p w\frac{\partial T}{\partial z}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)$$

Neglecting axial heat conduction

Type of equation? Elliptic---椭圆型！ (for *x*,*y*)

Z is a one-way coordinate like time!

That is at each z position the temperature in x-y plane should be solved simultaneously ! Thus: it is elliptic in x-y plane, and one-way (parabolic) in z-direction!

Boundary conditions: At the walls, $T=T_w$;

At the center line, $\partial T/\partial n=0$

3.6.2 Dimensionless governing equation

We should define an appropriate dimensionless temperature such that the dimension of the problem can be reduced from 3 to 2: Separating the one-way coordinate z from the two-way coordinates x, y 。

$$\Theta = \frac{T_w - T}{T_w - T_b} \leftarrow \frac{T - T}{T - T_b} \leftarrow \frac{T - T}{T - T}$$

Then $$T = \Theta(T_b - T_w) + T_w$$

$$\frac{\partial T}{\partial z} = \Theta \frac{\partial (T_b - T_w)}{\partial z}$$

$$\boxed{Pe = \frac{\rho c_p w_m D}{\lambda}}$$

Defining: $$X = x/D,\ Y = y/D,\ Z = z/(DPe)$$

One-way coordinate!

Dimensionless governing eq.

$$\frac{\partial (T_b - T_w)}{\partial Z}\frac{1}{T_b - T_w} = \frac{\dfrac{\partial^2 \Theta}{\partial X^2} + \dfrac{\partial^2 \Theta}{\partial Y^2}}{\dfrac{W}{W_m}\Theta} = -\Lambda$$

Dependent on Z only

Dependent on X, Y only

$\Lambda > 0$

Thus:

$$\begin{cases} \dfrac{\partial^2 \Theta}{\partial X^2} + \dfrac{\partial^2 \Theta}{\partial Y^2} + \Lambda \dfrac{W}{W_m}\Theta = 0; \\ \text{At the walls } \Theta = 0 \\ \text{At center lines}, \dfrac{\partial \Theta}{\partial n} = 0 \end{cases}$$

$$\frac{d (T_b - T_w)}{dZ}\frac{1}{T_b - T_w} = -\Lambda$$

Will be used for determining Nusselt number!

Heat conduction with an inner source!

3.6.3 Analysis on the unique solution condition

Because of the homogeneous character, these also exists an uncertainty of being magnifying by any times!

Introducing average temperature (difference):

$$T_w - T_b = \frac{\int_A (T_w - T)w\,dA}{\int_A w\,dA} \longrightarrow \frac{T_w - T_b}{T_w - T_b} = \frac{\int_A \frac{T_w - T}{T_w - T_b} w\,dA}{w_m A}$$

$$1 = \frac{1}{A}\int_A \frac{T_w - T}{T_w - T_b}\frac{w}{w_m}\,dA \longrightarrow 1 = \frac{1}{A}\int_A \Theta\left(\frac{W}{W_m}\right)dA$$

It is the additional condition for the unique solution.

Numerical solution method is the same as that for a circular tube.

3.6.4 Treatment of numerical results

After receiving converged velocity and temperature fields, friction factor and Nusselt number can be obtained as follows:

1.*fRe*— for laminar problems *fRe* =constant:

$$f\,\mathrm{Re} = [-\frac{D_e \frac{dp}{dz}}{\frac{1}{2}\rho w_m^2}](\frac{w_m D_e}{\nu})$$

Definition of W

$$W = \frac{\eta w}{-D^2 \frac{dp}{dz}}$$

$$f\,\mathrm{Re} = \frac{2}{W_m}(\frac{D_e}{D})^2$$

2. *Nu*— Making an energy balance ：

$\rho c_p w_m A \frac{dT_b}{dz} = qP$,$P$ is the duct circumference （周向） length

$$\frac{d(T_b - T_w)}{dZ}\frac{1}{T_b - T_w} = -\Lambda \quad \text{i.e.,} \quad \frac{dT_b}{dZ} = \frac{dT_b}{dz} DPe = (T_w - T_b)\Lambda$$

$$\frac{dT_b}{dz} = \frac{1}{DPe}(T_w - T_b)\Lambda$$

Substituting in $\rho c_p w_m A \dfrac{dT_b}{dz} = qP$

yields $q = \dfrac{A\rho c_p w_m}{P}\dfrac{dT_b}{dz} = \dfrac{A\rho c_p w_m}{P}\dfrac{1}{DPe}\Lambda(T_w - T_b)$

yields: $q = \dfrac{A}{P}\dfrac{\lambda}{D^2}\Lambda(T_w - T_b)$ $\boxed{Pe = \dfrac{\rho c_p w_m D}{\lambda}}$

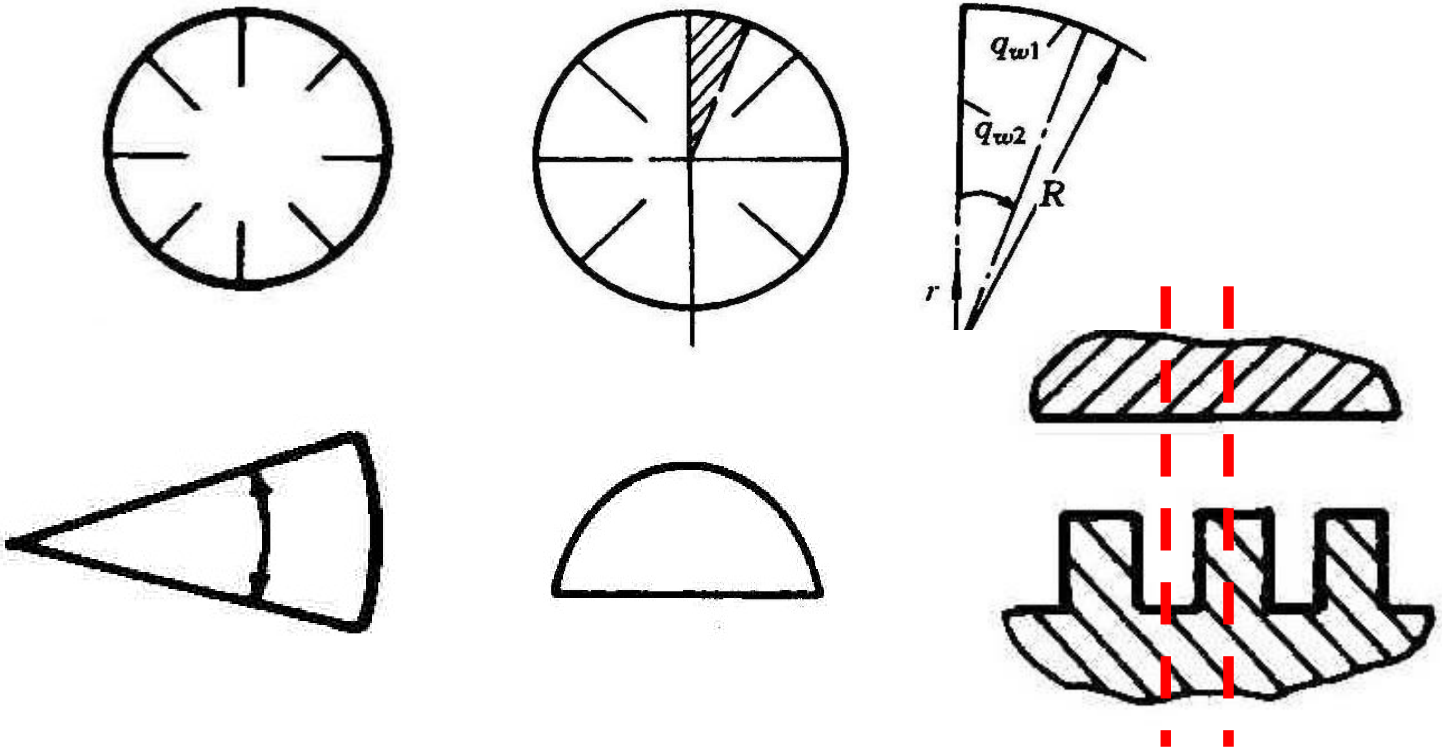
$$Nu = \frac{hD_e}{\lambda} = \frac{q}{T_w - T_b}\frac{D_e}{\lambda} = \frac{1}{T_w - T_b}\frac{D_e}{\lambda}\frac{A}{P}\frac{\lambda}{D^2}\Lambda(T_w - T_b)$$

$$D_e = \frac{4A}{P}$$

$$Nu = \frac{1}{4}\left(\frac{D_e}{D}\right)^2 \Lambda \qquad f\,\mathrm{Re} = \frac{2}{W_m}\left(\frac{D_e}{D}\right)^2$$

$$D_e = \frac{4A}{P}$$

3.6.5 Other cases



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同舟共济渡彼岸！

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