The Box Method

a Practical Procedure for Introduction of an Air Terminal Device in CFD Calculation

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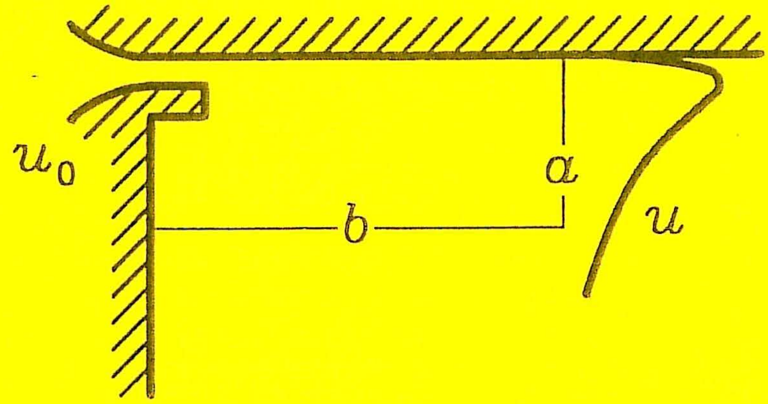

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by

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Abstract

The velocity level in a room ventilated by jet ventilation is strongly influenced by the supply conditions. The momentum flow in the supply jets controls the air movement in the room and, therefore, it is very important that the inlet conditions and the numerical method can generate a satisfactory description of this momentum flow. The Box Method is a practical method for the description of an Air Terminal Device which will save grid points and ensure the right level of the momentum flow.

Introduction

Figure 1 shows the decay of the maximum velocity in the flow that runs along the ceiling in a room with two-dimensional recirculating air movement. The velocity level obtained by two different inlet conditions, corresponding to two different supply openings, is retained in the flow along the ceiling. The difference in the velocity level will be retained in the occupied zone as well. A satisfactory description of the inlet conditions is, therefore, very important for the prediction of the flow in the whole room.

Figure 1 also shows that the velocity decay below the ceiling corresponds to the conditions in a wall jet, except close to the end wall opposite the supply opening. This means that the air movement below the ceiling can be expressed by parabolic equations, although the flow as a whole is recirculating and, therefore, described by elliptic equations. This strong upstream influence in the first part of the flow is the background for the wall jet description of boundary conditions for supply openings discussed in this paper.

The momentum flow in the wall jet below the ceiling controls the air movement in a room. For example, the maximum velocity in the occupied zone is proportional to the inlet velocity multiplied by the square root of the supply area, which expresses the square root of the supply momentum flow. Therefore, it is very important that the inlet conditions and the numerical method produce a satisfactory description of the momentum flow.

The supply momentum flow from diffusers depends on small details in the design. This means that a numerical prediction method should be able to handle small details in the order of a few millimetres to room dimensions of many metres. This wide range of geometry necessitates the use of many grid points and demands, therefore, a large computer or a procedure which can reduce the number of grid points.

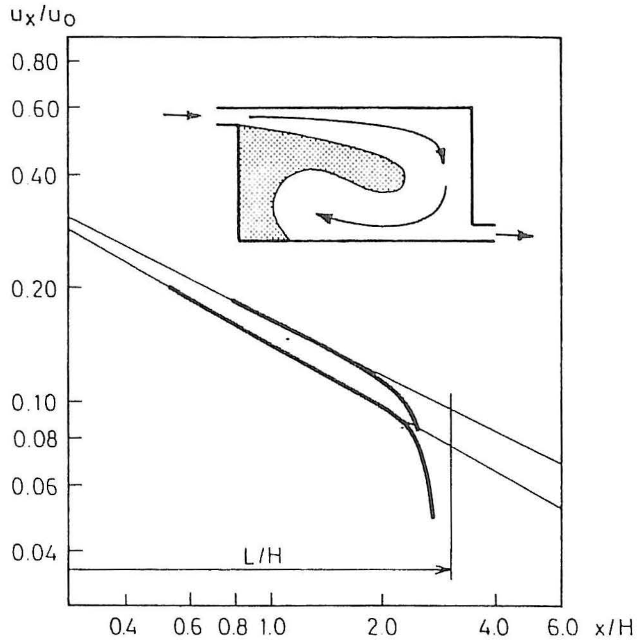

Figure 1. Velocity decay in the flow along the ceiling in a room. Predictions are shown for two different diffusers with the same slot height, h/H = 0.0015 and L/H = 3, where h, H and L are slot height, room height and room length, respectively.

The Box Method

Nielsen (1973) and (1978) was the first to use the Box Method in the numerical prediction of room air movement. This paper describes the method in the case of two-dimensional flow and will mainly be based on relevant chapters in the Ph.D. thesis "Flow in Air Conditioned Rooms" by Nielsen (1974). Other examples are given in (Nielsen 1975, 1989a, 1989b and 1992).

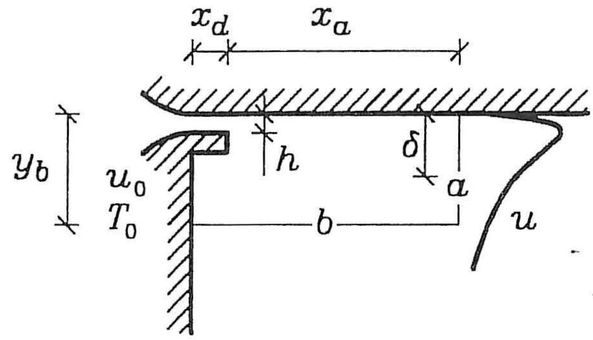

Figure 2. Location of boundary conditions by the Box Method.

Figure 2 shows the location of the boundary conditions around the diffuser used in the Box Method. The details of the flow in the immediate vicinity of the supply opening are ignored, and the supplied jet is described by values along the surfaces a and b, see figure 2. Two advantages are obtained by using these boundary conditions. First, it is not required to use a grid as fine as is the case with fully numerical prediction of the development from a inlet flow to a wall jet. Secondly, it is possible to make two-dimensional predictions for supply openings which are three-dimensional, provided that the jets develop into a two-dimensional wall jet or free jet at a certain distance from the openings.

The profiles for the variables ϕ at the surface a are the universal or the self-preserving profiles for the actual diffuser at the distance x_a, where ϕ corresponds to velocity u, temperature T, concentration c, turbulent kinetic energy k and turbulent dissipation ε, respectively.

The surface b in figure 2 shows the other boundary in the Box Method. A parallel flow is assumed at this surface $(\partial\phi / \partial y = 0)$.

The length x_a should be sufficient to locate the surface a in an area with a fully developed wall jet. The selection of a large x_a reduces both the gradients of the ϕ values at the surface a and the solution domain, which means a reduction in grid points and computation time. The length x_a should, on the other hand, only be a small fraction of the room length L because the velocity decay may be slightly influenced by the recirculating flow, and it has to be predicted by the elliptic equation.

The height $y_b^{\prime}$ of the surface a should be adequate for the momentum flow to be established in the wall jet. Figure 3 shows u_x / u_o versus y_b / δ, where u_o is the supply velocity, u_x is the maximum velocity in the wall jet and δ is the half width of the wall jet (thickness of the jet to the velocity $u_x / 2$). The figure indicates that $y_b / \delta = 0.75$ and $y_b / \delta = 1.0$ shows good results, while $y_b / \delta = 0.5$ is too small in the given situation. It is necessary to compare the velocity decay in the predictions with measured values, and it is necessary to check the continuity in all profiles in the point (x_a, y_b). It is not possible to use a large value of y_b / δ because the real profiles in the room are different from the universal wall jet profiles for $y_b / \delta > 1 - 1.5$.

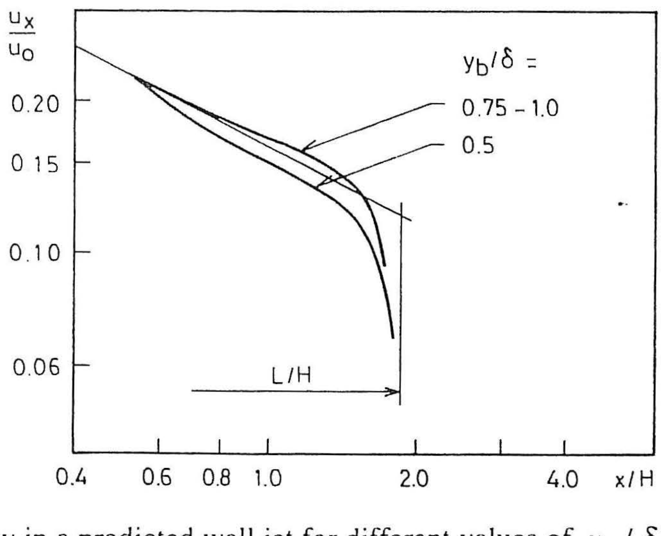

Figure 3. Velocity decay in a predicted wall jet for different values of y_b / δ. The velocity decay for $y_b / \delta = 1.0$ corresponds to measurements in the given situation. h/H = 0.003, L/H = 1.9 and Re = 1400.

The maximum velocity in the profile u_x at distance x_a is obtained from the K_p value of the diffuser, and δ is obtained from the D_p value of the diffuser. K_p and D_p values can be obtained from *commercial diffuser catalogues or design guide books* as ASHRAE Fundamentals (1997). The velocity profile can also be obtained from *measurements on the diffuser* used in the prediction. The use of the coefficients related to the actual diffuser is an important aspect of the Box Method because this procedure will ensure the correct profiles at surface a including the description of the momentum flow.

u_x and δ are connected to K_p and D_p in the following equations (Schwarz and Cosart, 1961).

$$\frac{u_x}{u_o} = K_p \left(\frac{h}{x_o + x_a} \right)^c \tag{1}$$

$$\frac{\delta}{h} = D_p \frac{x_o + x_a}{h} \tag{2}$$

The velocity profile at the surface a is given as a universal profile u / u_x, see e.g. Rajaratnam (1976) and Verhoff (1963).

The temperature level and the concentration level at surface a are influenced by the values crossing surface b due to entrainment. It is, therefore, necessary to calculate an energy balance and a mass fraction balance for the volume x_a times y_b in front of the diffuser in each iteration. The profiles are similar to the velocity profile except close to the wall where the values are constant corresponding to the minimum or the maximum value in the profile.

The maximum or the minimum temperature in the profile T_x is obtained from the K_{pT} value of the diffuser or from measurements on the diffuser. δ_T is obtained from the D_{pT} value of the diffuser or from measurements.

T_x and δ_T can be obtained from the following equations.

$$\frac{T_x - T_b}{T_o - T_b} = K_{pT} \left(\frac{h}{x_o + x_a} \right)^c \tag{3}$$

$$\frac{\delta_T}{h} = D_{pT} \frac{x_o + x_a}{h} \tag{4}$$

T_b is the surrounding temperature, i.e. the mean temperature along surface b in figure 2.

The distribution of turbulent kinetic energy k at surface a is given from measurements of $\overline{u'^2} / u_x^2$, $\overline{v'^2} / u_x^2$ and $\overline{w'^2} / u_x^2$, where $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{w'^2}$ are the turbulent normal stresses, see e.g. Nelson (1969).

The turbulent dissipation ε and the turbulent viscosity μ_t are found from the u, k and $\overline{u'v'}$ profiles, see Verhoff (1963) and Nelson (1969). The turbulent viscosity is given from the Boussinesq hypothesis

$$-\rho\ \overline{u'v'} = \mu_t \frac{\partial u}{\partial y} \tag{5}$$

where ρ is the density and $\overline{u'v'}$ is the turbulent shear stress. The equation assumes that there is a vanishing shear stress at the velocity maximum. This is not the case in asymmetrical jets such as wall jets where μ_t will follow the dotted line in figure 4 when it is calculated from equation (5).

The turbulent length scale ℓ is determined from the μ_t distribution and the k distribution according to the following equation

$$\ell = \mu_t \,/\, C_\mu k^{0.5} \rho \tag{6}$$

where C_μ is a constant or a variable in the case of low turbulent flow. The dotted curve in figure 5 shows the distribution of the length scale ℓ.

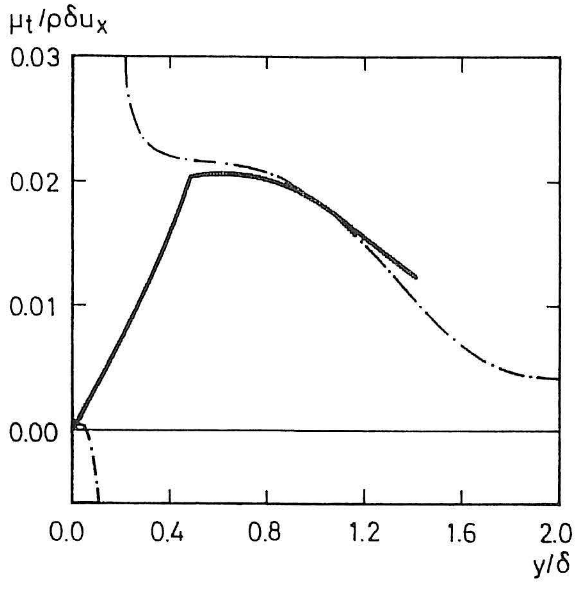

Figure 4. Distribution of turbulent viscosity in a two-dimensional wall jet.

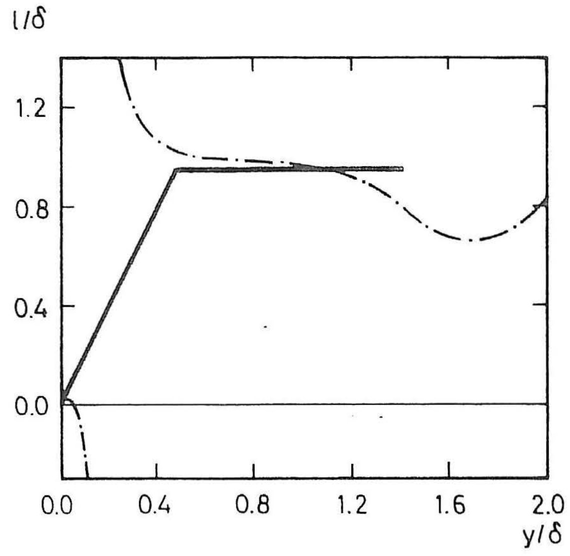

Figure 5. Distribution of the turbulent length scale in a two-dimensional wall jet.

The obtained value for μ_t and ℓ cannot be used as boundary values since they assume conditions which are disregarded in the turbulence model. New values are based on the length scale shown as an uninterrupted line in figure 5. This length scale is proportional to the distance from the wall up to $y/\delta = 0.5$, and it has a value close to the level found according to equation (5) for $y/\delta > 0.5$. If this length scale is used in equation (6) it is possible to obtain the μ_t distribution shown as an uninterrupted line in figure 4.

The new length scale ℓ is used to determine the distribution of dissipation along the surface a according to the equation

$$\varepsilon = k^{3/2} / \ell \tag{7}$$

It is also possible to use the Box Method in the case of special diffuser arrangements. Figure 6 shows the supply opening of a plane jet at a distance y_s from a parallel surface. Measurements made by Schwartzbach (1973) show that the jet is deflected due to the Coanda effect and develops into a wall jet at a distance x_a from the supply opening. The curves in figure 6 show the values for x_a/h, x_o/h, u_x/u_o and δ/h. Based on these data the boundary conditions for a wall jet are determined as before, though it must be pointed out that the turbulence is slightly higher in this case owing to the deflection of the jet.

Appendix A shows further examples of K_p, D_p and x_o/h values for different types of slot diffusers which can be used in the Box Method. The figures in Appendix A show the variety of supply openings, which can be simulated simply by changing the three values K_p, D_p and x_o.

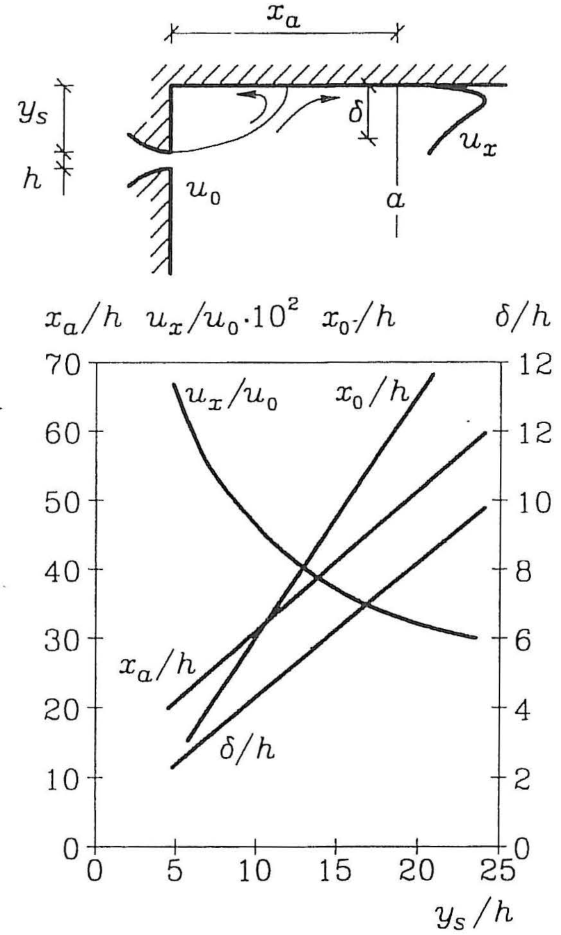

Figure 6. Two-dimensional jet supplied parallel to a surface. After Schwartzbach (1973).

Figure 7 illustrates the use of the Box Method in a special situation where three-dimensional boundary conditions close to the diffusers develop into a two-dimensional flow further downstream in the jet. The figure shows an example of measured and predicted isothermal velocity profiles in a room where the supply consists of 9 nozzles placed at the distance $H/4$ from the ceiling. The length of the room is three times its height and h/H is 0.011 where h is determined as the height in a slot giving the same supply area as the nozzles. The velocity profiles show that the supplied jets merge into a plane free jet which runs close to the ceiling in its further development forming a wall jet. The flow around the supply opening is strongly three-dimensional. However, the measurements show that the recirculating flow formed in the greater part of the room is two-dimensional. The measurements were made by Blum (1956).

The calculated velocity profiles in figure 7 are determined as a numerical solution of the two-dimensional flow equations. In the predictions the supply opening is characterized by the plane wall jet profile which it forms at the distance $x/H = 1.2$. It is seen that the agreement between the measured and the calculated velocities is good. The deviation of the maximum velocity in the occupied zone is below 1 % of the supply velocity. The agreement between the measured and the calculated velocity decay in the wall jet below the ceiling is also good. It is seen, however, that the calculated increase in the jet width barely reaches the measured value.

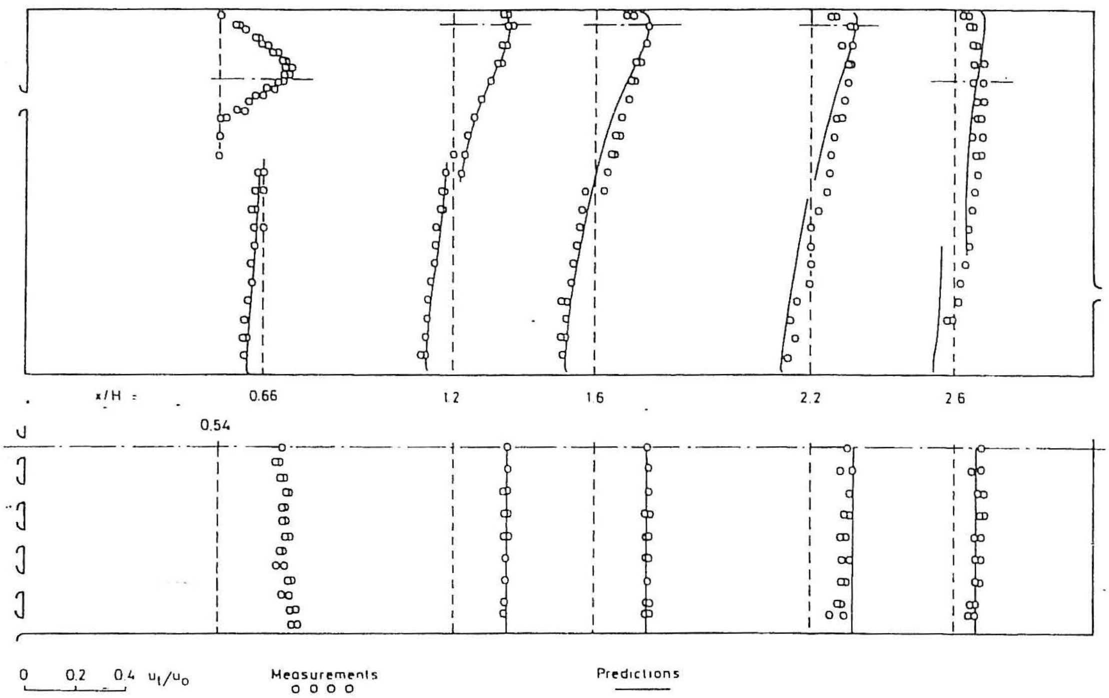

Figure 7. Measurements and predictions of velocity profiles in a room with nine supply nozzles placed at a certain distance from the ceiling. The upper figure shows a vertical section in the middle plane, and the lower figure shows a horizontal section at the heights shown in the upper figure. The calculated velocity u_t is the total velocity $\left(u^2 + v^2\right)^{0.5}$. $L/H = 3.0$, $W/H = 1.0$, $h/H = 0.011$ and the Reynolds number $Re = 25000$. L, H and W are the length, the height and the width of the room, respectively.

The use of a wall jet profile as the boundary value in the calculation in figure 7 is a good example of the simplification that can be achieved. If the actual supply openings had been used as boundary conditions, the calculations should have been performed by an equation system for three-dimensional flow with a strongly increased number of grid points close to the diffusers instead of the equation system for two-dimensional flow. However, this means a severe increase in both the computer storage and the computation time.

List of symbols

a	Control surface at supply opening
b	Control surface at supply opening
c	Concentration
C_μ	Constant in turbulence model
D_p	Growth rate for plane wall jet
D_{pT}	Growth rate for temperature profile
e	Exponent
h	Effective height of diffuser

H	Height of room
k	Turbulent kinetic energy
K_p	Velocity decay coefficient for a plane jet
K_{pT}	Temperature decay coefficient for a plane jet
ℓ	Turbulent length scale
L	Length of room
T_o	Supply temperature
T_x	Minimum or maximum temperature of wall jet
T_b	Mean temperature along surface b
u_x	Maximum velocity in wall jet
u_o	Supply velocity
u'	Instantaneous deviation from time averaged velocity
v'	Instantaneous deviation from time averaged velocity
w'	Instantaneous deviation from time averaged velocity
x_o	Distance to virtual origin of jet
x_a	Distance from diffuser to surface a
x_d	Distance from wall to diffuser
y_s	Distance from ceiling to supply opening
δ	Thickness of wall jet
δ_T	Thickness of temperature profile in jet
ε	Dissipation
μ_t	Turbulent viscosity
ρ	Density
ϕ	Variable $(u, T, c, k, \varepsilon)$

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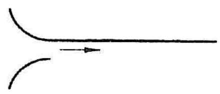
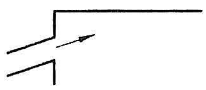
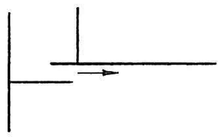
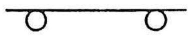
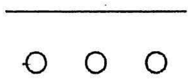
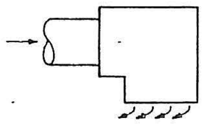
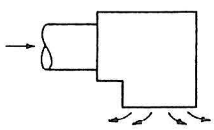
Appendix A

Slot diffusers

Reference	K_p	D_p	x_o/h	e	Geometry
Schwarz and Cosart (1961)	5.4	0.068	11.2	0.555	
Myers et al. (1963)	7.05	0.07	14.0	0.63	
Hanel and Scholtz (1978)	3.55	0.087	20.0	≡ 0.5	$Tu < 1$ %
	3.46	0.104	31.1	≡ 0.5	$Tu > 40$ %
Förthmann (1934)	4.1	0.082	6.6	0.5	
Hestad (1974)	3.1	0.10	34.0	≡ 0.5	
Hestad (1974)	3.6		≡ 0	≡ 0.5	
Blum (1956)	3.32	0.111	-2.65	≡ 0.5	
	3.16	0.128	-30.25	≡ 0.5	
	2.97	0.135	56.59	≡ 0.5	
Nielsen and Möller (1988)	2.35	0.16		0.5	$Re = 2660$ 
	2.35	0.10	18.3	0.5	$Re = 4140$
	2.35	0.08	17.7	0.5	$Re = 5610$
	2.35	0.16		0.5	$Re = 1330$ 
	2.49	0.14	16.3	0.5	$Re = 2070$
	2.69	0.06	49.5	0.5	$Re = 2750$

Appendix B

The Box Method

Fortran listing of elements of the Box Method (Nielsen et al. 1978).

```
      COMMON
     1/COM3/IW,JW,IWM1,IWP1,JWM1,JWP1,XZERO,XD,CUIN,EUIN,CDEL,CTEMP,
     2      ETA(33),FETA(33),FIETA(33),ZKETA(33),
     3      UMP,UPWJ(25),STU(25)
C
CHAPTER  1  1  1  1  CALCULATION OF WALL JET VALUES  1  1  1  1  1
C
C-----WALL JET PROFILE
C     DATA FROM REPRT 626, MAY 63, PRINCETON UNIVERSITY
C     CO-ORDINATES
      DATA ETA/   .01,.02,.03,.04,.05,.06,.07,.08,.09,.1,.12,.14,.16
     1,.18,.2,.3,.4,.5,.6,.7,.8,.9,1.,1.1,1.2,1.3,1.4,1.5,1.6,1.7,1.8
     2,1.9,2./
C     VELOCITY PROFILE
      DATA FETA/   .76,.833,.876,.906,.927,.944,.958,.968,.977,.983
     1,.993,.998,1.,.999,.997,.964,.911,.847,.778,.706,.635,.566,.5
     2,.438,.380,.327,.279,.236,.198,.165,.136,.111,.09/
C     STREAM FUNCTION DISTRIBUTION
      DATA FIETA/   .007,.015,.023,.032,.041,.051,.06,.07,.08,.089
     1,.109,.129,.149,.169,.189,.287,.381,.469,.55,.625,.692,.752
     2,.805,.852,.893,.928,.958,.984,1.006,1.024,1.039,1.051,1.061/
C     TURBULENT KINETIC ENERGY
      DATA ZKETA/.0346,.0350,.0356,.0360,.0366,.0371,.0379,.0382,.0386
     1,.0388,.0395,.0402,.0409,.0416,.0424,.0478,.0529,.0562,.0578
     2,.0573,.0548,.0503,.0452,.0398,.0333,.0271,.0211,.0154,.0116
     3,.0082,.0057,.0040,.0029/
C-----COEFFICIENTS FOR WALL JET
      CUIN=5.395
      EUIN=-0.555
      CDEL=0.0678
      XZERO=11.2*RSMALL
      XD=0.0
C-----MAX VELOCITY IN JET. UM FOR XU(IW) AND UMP FOR X(IW)
      UM=UIN*CUIN*(XU(IW)/RSMALL+XZERO/RSMALL-XD/RSMALL)**EUIN
      UMP=UIN*CUIN*((X(IW)+XZERO-XD)/RSMALL)**EUIN
C-----BOUNDARY LAYER, DELTA (VEL.=UM/2)
C     DELU= DELTA FOR U-VELOCITY, DELP= DELTA FOR OTHER VARIABLES
      DELU=CDEL*(XU(IW)-XD+XZERO)
      DELP=CDEL*(X(IW)-XD+XZERO)
C-----GENERATING STREAM FUNCTION DISTRIBUTION
      DO 10 J=2,JW
      JP1=J+1
      ET=YV(JP1)/DELU
      DO 20 L=1,33
      IF(ET.LE.ETA(L)) GO TO 30
 20   CONTINUE
 30   DIFE=(ET-ETA(L-1))/(ETA(L)-ETA(L-1))
      STU(JP1)=FIETA(L-1)+(FIETA(L)-FIETA(L-1))*DIFE
      STU(JP1)=STU(JP1)*DELU*UM
```

```
C-----GENERATING OF PROFILES FOR OTHER VARIABLES
      ETP=Y(J)/DELP
      DO 40 L=1,33
      IF(ETP.LE.ETA(L)) GO TO 50
 40   CONTINUE
 50   DIFE=(ETP-ETA(L-1))/(ETA(L)-ETA(L-1))
      TE(IW,J)=ZKETA(L-1)+(ZKETA(L)-ZKETA(L-1))*DIFE
      TE(IW,J)=TE(IW,J)*UMP*UMP
      UPWJ(J)=FETA(L-1)+(FETA(L)-FETA(L-1))*DIFE
      XL=2.*Y(J)
      IF(XL.GT.0.95*DELP) XL=0.95*DELP
      VIS(IW,J)=CMU*DENSIT*XL*(TE(IW,J)**0.5)
      ED(IW,J)=(TE(IW,J)**1.5)/XL
 10   CONTINUE
C-----GENERATING VELOCITY PROFILE
C        ACCORDING TO VOLUME FLOW IN WALL JET
      STU(2)=0.0
      DO 55 J=2,JW
   55 U(IW,J)=(STU(J+1)-STU(J))/SNS(J)
C
CHAPTER  2  2  2  2  2  CALCULATION OF ENTRAINMENT VELOCITY  2  2  2
C
C-----TOTAL VOLUME FLOW IN WALL JET
      FLOWW=STU(JW)
C-----MEAN ENTRAINMENT VELOCITY
      DO 100 I=2,IWM1
 100  V(I,JW)=-(FLOWW-FLOWIN/DENSIT)/XU(IW)
      RETURN
      END
```

Energy balance for the volume x_a times y_b , see page 4.

```
C-----WALL JET AREA
C       DT/DY=0 ALONG ENTRAINMENT BORDER
        DO 520 I=2,IWM1
        DO 520 J=2,JWM1
  520   T(I,J)=T(I,JW)
C       SURROUNDING MEAN TEMPERATURE TO WALL JET
        TEM=0.0
        DO 530 I=2,IWM1
        TEP=T(I,JW)*SEW(I)
  530   TEM=TEM+TEP
        TEM=TEM-T(IWM1,JW)*SEW(IWM1)/2.0
        TEMP=TEM/X(IWM1)
C-----HEAT FLOW INTO WALL JET (TIN=0.0 REF. TEMP.)
        HWJIN=0.0
        DO 532 I=2,IWM1
        HWJ=DENSIT*CPP*V(I,JWP1)*T(I,JWP1)*SEW(I)
  532   HWJIN=HWJIN+HWJ
C-----HEAT BALANCE IN WALL JET
        HSLOT=DENSIT*CPP*UIN*TIN*RSMALL
        HWJOUT=HSLOT-HWJIN
        HOUT1=0.0
        HOUT2=0.0
        DO 540 J=2,JW
        ETP=Y(J)/(CDEL*(X(IW)-XD+XZERO))
        HOUT1=HOUT1+DENSIT*CPP*U(IW,J)*TEMP*SNS(J)
        HWJ=DENSIT*CPP*U(IW,J)*UPWJ(J)**PRANDT*SNS(J)
        IF(ETP.LT.0.16) HWJ=DENSIT*CPP*U(IW,J)*SNS(J)
  540   HOUT2=HOUT2+HWJ
C       MAXIMUM TEMPERATURE DIFFERENCE IN WALL JET
        DTM=(HWJOUT-HOUT1)/HOUT2
        IF(DTM/(TIN-TEMP).LT.0.0) DTM=0.0
        IF(DTM/(TIN-TEMP).GE.1.0) DTM=0.99*(TIN-TEMP)
C       TEMPERATURE PROFILE
        DO 550 J=2,JW
        ETP=Y(J)/(CDEL*(X(IW)-XD+XZERO))
        T(IW,J)=TEMP+DTM*UPWJ(J)**PRANDT
  550   IF(ETP.LT.0.16) T(IW,J)=TEMP+DTM
C       CALCULATION OF CTEMP
        CTEMP=DTM/(TIN-TEMP)/(UMP/UIN)
C       MAINTAINING CALCULATED TEMPERATURES IN WALL JET AREA
        DO 560 I=2,IW
        DO 560 J=2,JWM1
        SU(I,J)=GREAT*T(I,J)
  560   SP(I,J)=-GREAT
```

ETA ~ η

FETA ~ $f(\eta)$ $\quad (= u / u_s)$

FIETA ~ $\int_o^\eta f(\eta)$

ZKETA ~ k / u_s^2

CUIN ~ K_p

EUIN ~ e

CDEL ~ D_p

XZERO ~ x_o

RSMALL ~ h

UIN ~ u_o

XD ~ x_d

UM ~ u_s for u velocity

UMP ~ u_s for other variables

DELU~ δ for u velocity

DELP ~ δ for other variables

EP ~ η $\quad (= y / \delta)$ for u velocity

ETP ~ η $\quad (= y / \delta)$ for other variables

STU(JP1) ~ Stream function

TE(IW,J) ~ k

VIS(IW,J) ~ μ_t

XL ~ ℓ

UPWJ(J) ~ u / u_s

ED(IW,J) ~ ε

U(IW,J) ~ u velocity at surface a

V(I,JW) ~ entrainment flow at surface b

T(I,J) ~ temperature

DTM ~ ΔT_s

PRANDT ~ σ_h

T(I,JW) ~ temperature at surface b