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Posted Date: 18 November 2024

doi: 10.20944/preprints202411.1211.v1

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Article

Code Revival: Fluid Motion in a Curved Pipe

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Abstract: This paper presents a revival of FORTRAN 66 code which calculates flow through curved pipes. Results from the code were originally presented in [Greenspan, D. Secondary flow in a curved tube. *J. Fluid Mech.* **1973**, *57*, 167-176]. We demonstrate a step-by-step code revival process and compare original (coarse) results to updated (fine) solutions. The purpose of our paper is to make the code available as modern Fortran for the scientific community. The code runs quickly on modern hardware architectures and enables fast understanding of the physical effects included.

Keywords: fluid motion in a curved pipe; laminar flow; code revival; FORTRAN 66; modern Fortran

1. Introduction

The theoretical treatment of laminar flow in curved pipes was pioneered by Dean in the late 1920s [1,2]. He showed that in addition to a displacement of streamwise flow, a secondary flow also exists, taking the form of two vortices, the so-called Dean vortices. A constant D , the Dean number, was identified as the key parameter:

$$D = 4Re\sqrt{\frac{2a}{L}}, \quad (1)$$

where Re is the bulk Reynolds number, a is the pipe radius and L is the radius of curvature of the curved pipe. Dean [1] obtained simplified equations of motion for the approximation $a/L \ll 1$, which can be interpreted as $a/L \leq 0.01$ [2].

Dean [1] obtained theoretical solutions to the equations for the range $0 \leq D \leq 96$ and following this, McConlogue and Srivastava expanded the solutions numerically to $96 \leq D \leq 605.72$ [3]. In this paper we treat a subsequent study by Greenspan and Schubert [4,5], where numerical solutions were extended to $D \leq 5000$. This extension was done with a FORTRAN 66 code which is available as an Appendix in [4]. The purpose of our paper is to convert - and thus revive - this code to modern Fortran. The reason for this is twofold: (i) we need the revived code for planned future research and (ii) we want to make this code available to the scientific community for others who may need a fast and efficient code to calculate basic solutions of laminar flow in slightly curved pipes.

On a personal note, I have previous experience writing and running FORTRAN 77 code on an IBM mainframe at JET [6] during the period 1997-1998. Thus, the task at hand, to convert FORTRAN 66 code, was feasible.

The paper is structured as follows: In Section 2, we detail the FORTRAN 66 code revival steps; results from the revived code are presented in Section 3. A brief discussion is presented in Section 4 and finally we conclude in Section 5.

2. Code Revival

There were three aspects to the code revival, and they are treated in the three subsections below:

1. Digitise the scanned document
2. Convert the FORTRAN 66 code to modern Fortran
3. Debugging and testing of the code

2.1. Digitisation

We note that the original FORTRAN 66 code is only available in [4] and not available in the official journal paper [5]. As can be seen, the scanned document [4] has a quite poor quality, making in

challenging to perform the optical character recognition (OCR) needed. However, with 12 pages (~600 lines) of code, it would be very cumbersome to retype the code entirely by hand

We did not attempt to improve the quality of the scanned document before conversion.

Our initial attempts at extracting characters from the scanned document was done using Python with EasyOCR [7] and PyTesseract [8]. However, these tools performed poorly on the document.

Our next attempt was with two online converters [9,10]. The results were better than for the Python tools, but still with a correct percentage of around 50%.

The best conversion, with a success rate of roughly 80%, was the Amazon Textract tool from Amazon Web Services (AWS) [11].

In the end, we used the AWS tool to generate the initial digital file and combined it with the output from the two online converters. And finally, a human correction was needed for around 10% of the code.

2.2. Conversion

Once the code was available in digital form, the main conversion from FORTRAN 66 to modern Fortran was to replace the Hollerith string and data notation [12]. To achieve this goal, we also used ChatGPT-4 [13] to convert the Hollerith commands to modern Fortran.

2.3. Debugging and testing

At this stage we had a complete code available, the final step being to debug and test the code.

We chose to use a laptop with Microsoft Windows 11 [14] installed. Microsoft Visual Studio [15] was installed as the graphical user interface along with the Intel Fortran Compiler (ifx) [16]. In terms of Fortran versions, ifx uses the latest standards from Fortran 2018 and some Fortran 2023 features. In that sense, we consider the updated code to represent modern Fortran.

What remained was to compile (build solution) and systematically resolve the errors. Some sections were updated, for example replacing the reading of and writing on punch cards with files. Another major change was to make an IF statement to loop over all D values analysed in [4,5].

The final result of the steps is the modern Fortran code provided in Appendix A.

3. Results

All post processing in this section was done using GNU Octave [17].

3.1. Comparison to Original Findings

We include two figures with contour plots of ϕ and w , Figures 1 and 2, to facilitate a direct comparison to Figures 3 and 4 in [5]. Here, ϕ is the non-dimensional stream function for the secondary flow and w is the non-dimensional velocity in the streamwise direction. Only the upper half of the pipe is calculated by the Fortran code, we mirror this to the lower half for clarity of exposition. 0 (180) degrees indicate the outboard (inboard) positions, respectively.

The results match the original results very well, both in position and magnitude. Again, the ϕ curves move clockwise up to $D = 500$ and then counter-clockwise for larger D . And a certain waviness is observed for the core w curves for $D = 5000$, which was speculated to perhaps indicate a beginning transition to turbulence [5].

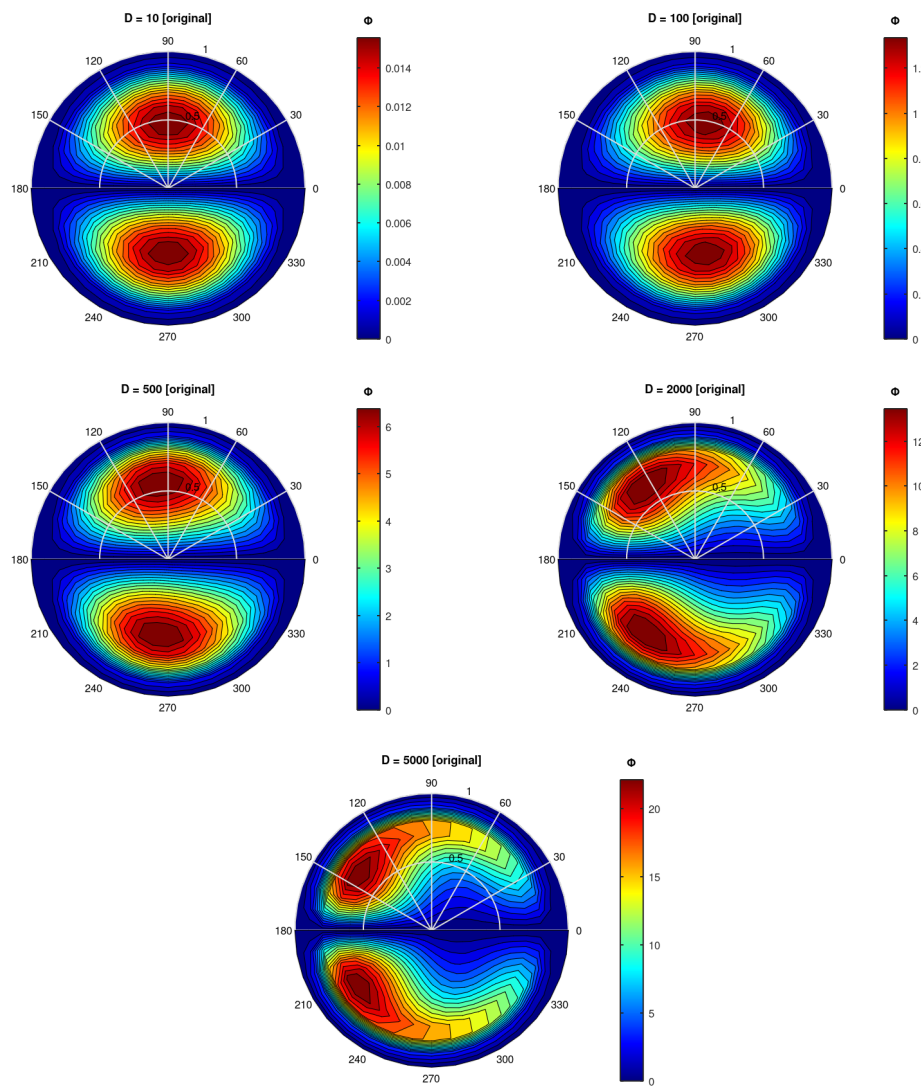


Figure 1. Original ϕ contour plots for $D = 10$, $D = 100$, $D = 500$, $D = 2000$ and $D = 5000$.

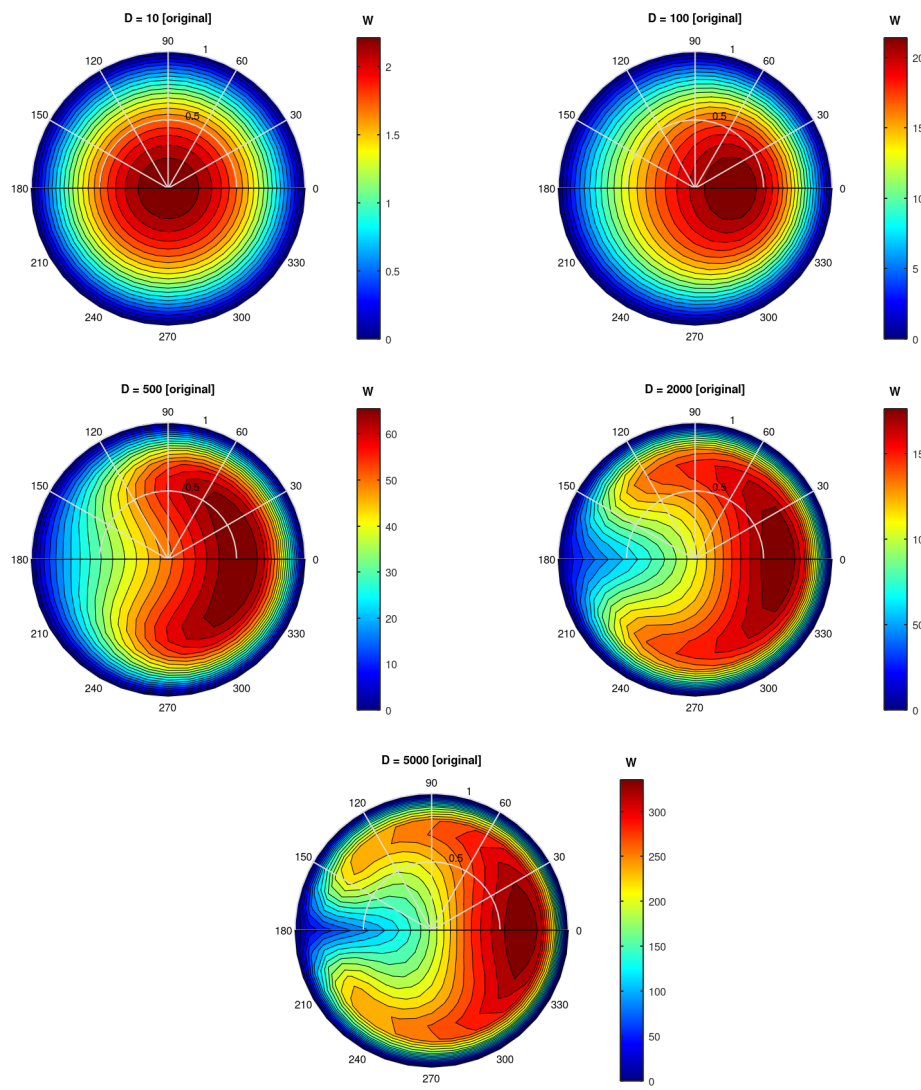


Figure 2. Original w contour plots for $D = 10, D = 100, D = 500, D = 2000$ and $D = 5000$.

3.2. Improvements

Having a complete modern Fortran code available enables improvements to e.g. the computational grid resolution. The original resolution was $\Delta r = 0.1$ and $\Delta\phi = \frac{\pi}{18}$. In the code in Appendix A, these resolutions are named NR and NA, respectively. We updated the code to run with double resolution, both for r and ϕ . To distinguish the grid resolutions, we call them "original" and "updated".

We compare original and updated contour plots for ϕ and w in Figures 3 and 4. The two largest values of D are compared; qualitatively, the results are very similar, although the contours of the updated resolution are more smooth than those of the original resolution.

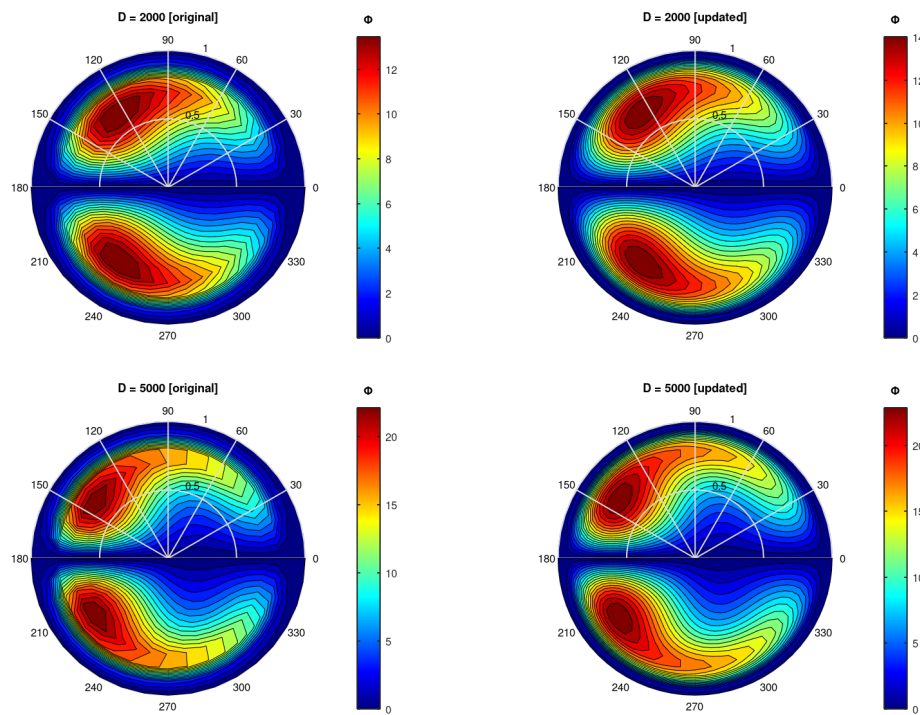


Figure 3. ϕ contour plots for $D = 2000$ and $D = 5000$. Left-hand column: Original (coarse) resolution, right-hand column: Updated (fine) resolution.

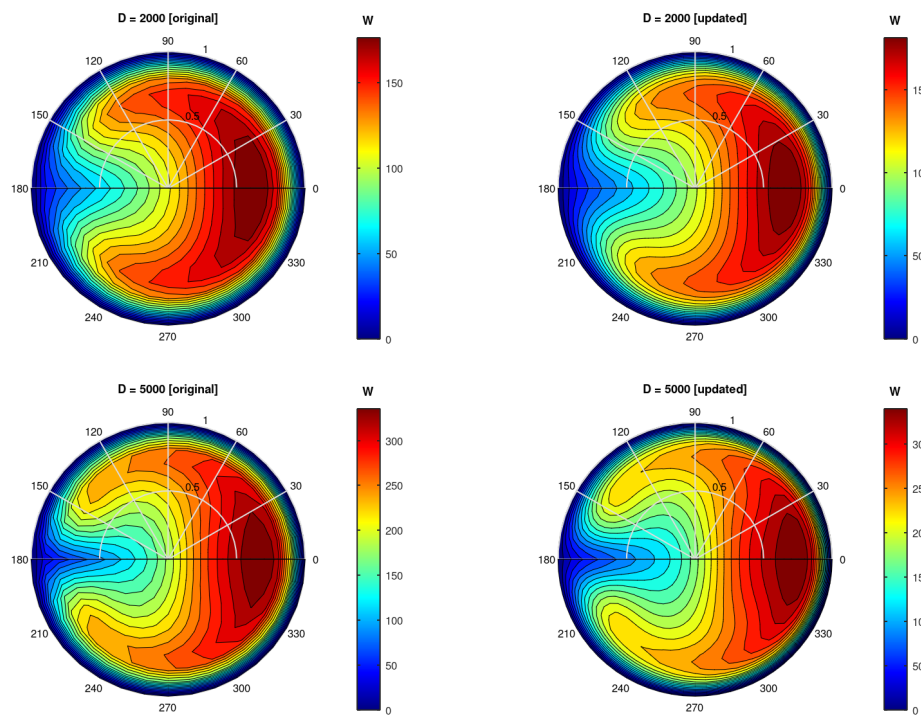


Figure 4. w contour plots for $D = 2000$ and $D = 5000$. Left-hand column: Original (coarse) resolution, right-hand column: Updated (fine) resolution.

A topic of interest for our future research is how the peak w value ($w_{\max}$) moves as a function of D . This is shown in Figure 5, where both the position and magnitude of $w_{\max}$ are included. The values are compared for the original and updated resolution; we observe that there is a substantial difference in the maximum position, but not in the maximum value of w . For reference, $w_{\max}$ values from [3] are included, which agree with the present values for smaller values of D , but deviate for larger D .

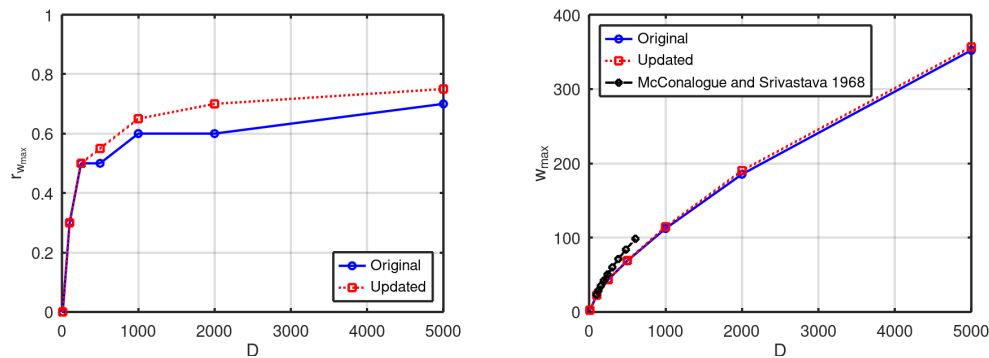


Figure 5. Left-hand plot: Normalised radius for maximum streamwise velocity $w_{\max}$ as a function of D , right-hand plot: Value of $w_{\max}$ as a function of D .

An important effect of the secondary flow is the blockage effect, i.e. that it obstructs the streamwise flow. This is also calculated in the Fortran code and shown in Figure 6. Here, the flux (or flow rate) is normalised to that of a straight pipe.

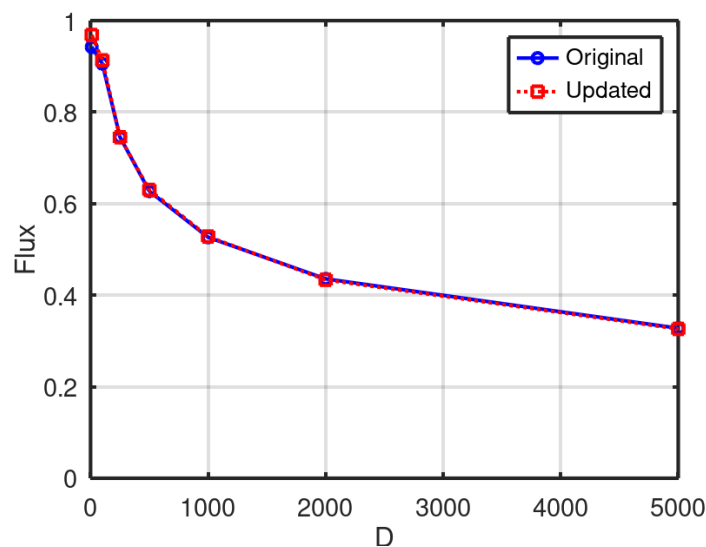


Figure 6. Streamwise flux as a function of D .

4. Discussion

It has been discussed whether flow in curved pipes only depends on the Dean number, or if one should separate studies into separate Re and curvature effects. Now it is indeed clear that such a separation is important for turbulence studies, see e.g. [18]. For the case we treat with slightly curved pipes, the transition to turbulence is subcritical, which is the same as for straight pipes.

From experimental investigations with higher curvature [19], it is interesting to note the persistence of structures in turbulent flow similar to those identified in laminar flow. Perhaps the laminar flow structures form a skeleton/seed which turbulence builds on?

5. Conclusions

In this paper, we have presented a case study on how to revive older code (FORTRAN 66) to modern Fortran. This code revival has enabled fast calculations of laminar flow through slightly curved pipes. The basis was [5], with the original code being provided in [4]. We hope that our work serves as a template and inspiration for other scientists who have a need for bringing older code back to life again. Also, the modern Fortran code in Appendix A is now available to the scientific community as a fast method to obtain a physical picture of streamwise and secondary flow in curved pipes.

After the code was operational, we tested increasing the grid resolution and found that the position of the maximum streamwise velocity as a function of D was sensitive to this change.

The code can be modified in other ways to e.g. extract information on the stream function for the secondary flow or to make a more detailed study using smaller steps in D .

We plan to use the code in the future to facilitate interdisciplinary work on fluids and plasmas which was initiated in [20].

Funding: This research received no external funding.

Data Availability Statement: The data presented in this paper can be generated by using the modernised Fortran code in Appendix A.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A Modernised Fortran Code

This appendix includes the modernised Fortran version of the original FORTRAN 66 code written by A.B.Schubert in 1972 [4].

Compiling and running the solution creates a separate file for each value of D .

```

C:\Temp\v2_Schubert_FORTRAN_66_1972.f 1
C   Appendix: FORTRAN Program for Secondary Flow, by A. B. Schubert (1972)
C
C   Nils T. Basse (2024):
C       Updates to remove obsolescent features (Hollerith strings and
C       data) and to write results to files instead of to punch cards.
C   Other changes marked by "NTB 2024" below.
C
C   TUBEFLOW   A PROGRAM WHICH COMPUTES THE SECONDARY
C   (CROSS-SECTIONAL) FLOW OF A FLUID IN A CURVED TUBE AND THE
C   VELOCITY AND FLUX IN THE AXIAL DIRECTION OF THE TUBE BY
C   DISCRETIZATION OF THE CROSS-SECTION AND OF THE GOVERNING
C   DIFFERENTIAL EQUATIONS.
C
C   NTB 2024:
C   Original (coarse) resolution: NR=10,NA=18
C   Updated (fine) resolution:   NR=20,NA=36
C   PARAMETER NR=10,NA=18,NRP1=NR+1,NAP1=NA+1,NRM1=NR-1,NAM1=NA-1,
C   * NAH=NA/2+1
C
C   NR = NUMBER OF GRID SPACES ON (0,1) IN RADIAL (R) DIRECTION.
C   NA = NUMBER OF GRID SPACES ON (0,PI) IN ANGULAR (ALPHA)
C   DIRECTION.
C
C   PRINCIPAL DISCRETE FUNCTIONS COMPUTED ARE DEFINED AS FOLLOWS.
C   PHI(I,J,K) = NON-DIMENSIONAL STREAM FUNCTION VALUE FOR SECONDARY
C               FLOW AT POLAR GRID POINT CORRESPONDING TO I-TH
C               RADIAL VALUE (WHERE I= 1 CORRESPONDS TO R = 0 AND
C               I = NR+1 CORRESPONDS TO R = 1) AND J-TH ANGULAR
C               VALUE (WHERE J = 1 CORRESPONDS TO ALPHA = 0 AND
C               J = NA+1 CORRESPONDS TO ALPHA = PI.
C               K = 1 IMPLIES A VALUE AT THE PREVIOUS OUTER
C               ITERATION.
C               K = 2 IMPLIES A VALUE AT THE PREVIOUS SOR ITERATION
C               K = 3 IMPLIES A VALUE AT THE CURRENT SOR AND OUTER
C               ITERATION.
C   W(I,J,K) = NON-DIMENSIONAL VELOCITY IN THE AXIAL DIRECTION,
C               WITH SUBSCRIPTS DEFINED AS FOR PHI.
C   OMEGA(I,J,K) = INTERMEDIATE VARIABLE INTRODUCED IN ANALYTICAL
C               DESCRIPTION OF PROBLEM, WITH SUBSCRIPTS DEFINED
C               AS FOR PHI.
C
C   DIMENSION PHI(NRP1,NAP1,4),W(NRP1,NAP1,4),OMEGA(NRP1,NAP1,4),
C   * XI(4),RHO(3),EPS(3),SA(NAP1),COSA(NAP1),RINV(NRP1),RINV2(NRP1),
C   * RHOC(3),B(NRP1,5),C(NRP1,NAP1),EPPS(3),XIC(4),E(NRP1,NAP1,6),
C   * EE(NRP1),EF(NRP1),CA(NRP1,NAP1),DELA(NR),CO(NR),DOR(3)
C
C   NTB 2024:
C   MAXSOR and MAXOUT increased by a factor of ten for fine resolution
C   DATA PI/3.14159255/,MAXSOR,MAXOUT/2500,600/,
C   * NOR/3/, (DOR(I),I=1,3)
C   */.2,.2,.2/
C
C   NTB 2024:

```

```

C:\Temp\v2_Schubert_FORTTRAN_66_1972.f 2
C      Added definitions to write files
      CHARACTER (LEN=10) :: file_id
      CHARACTER (LEN=50) :: file_name
      INTEGER::ctr

C      MAXSOR = MAXIMUM NUMBER OF ITERATIONS TO BE ALLOWED FOR COMPUTING
C              SOLUTION TO ANY SYSTEM BY SUCCESSIVE OVER-RELAXATION
C      MAXOUT = MAXIMUM NUMBER OF OUTER ITERATIONS TO BE ALLOWED IN THE
C              COMPUTATION OF PHI, W, AND OMEGA.
C      NOR = NUMBER OF DIFFERENT OVER-RELAXATION FACTORS TO BE TRIED
C            IN ANY DATA CASE.
C      DOR(I) = AMOUNT OF DECREASE IN OVER-RELAXATION FACTOR AT I-TH
C              CHANGE.

      KRP1=NRP1

C      DR = GRID SPACING IN RADIAL DIRECTION.
C      DA = GRID SPACING IN ANGULAR DIRECTION.

      DR=1./NR
      DA=PI/NA
      DAH=.5*DA
      DRH=.5*DR
      DRDAM=DR*DA
      DRDA=DR/DA
      DADR=DA/DR

C      COMPUTE ELEMENTS OF AREA, DELA(I),I=1,...,NR, IN RADIAL DIRECTION
C      FOR USE IN FLUX CALCULATION.

      DO 1 I=1,NR
1  DELA(I)=(2*I-1)*DRH*DRDAM

C      ON THE GRID DEFINED BY DR AND DA, COMPUTE DISCRETE FUNCTIONS
C      DEPENDENT ONLY ON RADIUS AND ANGLE.

      SA(1)=0.
      DO 2 J=2,NA
      SA(J)=SIN((J-1)*DA)*DAH
2  COSA(J)=COS((J-1)*DA)
      SA(NAP1)=0.
      COSA(NAP1)=-1.
      RINV(NRP1)=1.
      RINV2(NRP1)=1.
      DO 3 I=2,NR
      RINV(I)=1./((I-1)*DR)
      DRRH=DRH*RINV(I)
      RINV2(I)=RINV(I)**2
      DO 3 J=2,NA
3  CA(I,J)=DRRH*COSA(J)

C      COMPUTE SOR COEFFICIENTS FOR PHI.

```

C:\Temp\v2_Schubert_FORTTRAN_66_1972.f

3

```

DO 4 I=2,NR
  BO=2.*(DADR+DRDA*RINV2(I))+DA*RINV(I)
  B(I,1)=(DADR+DA*RINV(I))/BO
  B(I,2)=DRDA*RINV2(I)/BO
  B(I,3)=DADR/BO
  B(I,4)=B(I,2)
4 B(I,5)=DRDAM/BO

C      READ OUTER ITERATION SMOOTHING PARAMETERS (XI), OVER-RELAXATION
C      FACTORS (RHO), OUTER ITERATION CONVERGENCE TOLERANCES (EPS),
C      PARAMETER RELATED TO REYNOLDS NO. (D), AND INPUT/OUTPUT CONTROL
C      VARIABLES DEFINED AS FOLLOWS.
C      ISAVE.NE.0 IMPLIES SAVE THE SOLUTION FOR THIS CASE (IF OBTAINED)
C              IN MEMORY FOR USE AS STARTING VALUES FOR A SUCCEEDING
C              CASE WITH A DIFFERENT VALUE OF D.
C      ISAVE.EQ.0 IMPLIES DO NOT DO THE ABOVE.
C      IUSE.NE.0 IMPLIES TAKE STARTING VALUES FOR OUTER ITERATION FROM
C              MEMORY.
C      IUSE.EQ.0 IMPLIES INITIALIZE OUTER ITERATES TO ZERO.
C      IPCH.NE.0 IMPLIES WRITE SOLUTION FOR THIS CASE (IF OBTAINED)
C              TO FILE
C      IPCH.EQ.0 IMPLIES DO NOT WRITE SOLUTION OBTAINED FOR THIS CASE
C              TO FILE.

C      NTB 2024:
C      Save solution to memory
C      Take starting values from memory
C      Write solution to file
      ISAVE=1
      IUSE=1
      IPCH=1

C      NTB 2024:
C      Set initial conditions for all cases treated
      ctr=0
5 ctr=ctr+1
      IF (ctr==1) THEN
        D=10
        EPS(1)=10.**(-5.)
        EPS(2)=10.**(-3.)
        EPS(3)=10.**(-4.)
        RHO(1)=1.5
        RHO(2)=1.8
        RHO(3)=1.5
        XI(1)=0.1
        XI(2)=0.1
        XI(3)=0.1
        XI(4)=0.1
      ELSE IF (ctr==2) THEN
        D=100
        EPS(1)=2.*10.**(-4.)
        EPS(2)=5.*10.**(-3.)
        EPS(3)=5.*10.**(-3.)

```

C:\Temp\v2_Schubert_FORTRAN_66_1972.f

4

```

      RHO(1)=1.5
      RHO(2)=1.7
      RHO(3)=1.5
      XI(1)=0.1
      XI(2)=0.1
      XI(3)=0.1
      XI(4)=0.1
      ELSE IF (ctr==3) THEN
        D=250
        EPS(1)=2.*10.**(-3.)
        EPS(2)=2.*10.**(-2.)
        EPS(3)=4.*10.**(-2.)
        RHO(1)=1.5
C      NTB 2024:
C      RHO(2) changed from 1.8 (iteration 1), then 1.5
C      to 1.5 for all iterations
        RHO(2)=1.5
        RHO(3)=1.5
        XI(1)=0.1
        XI(2)=0.1
        XI(3)=0.1
        XI(4)=0.1
      ELSE IF (ctr==4) THEN
        D=500
        EPS(1)=4.*10.**(-3.)
        EPS(2)=4.*10.**(-2.)
        EPS(3)=8.*10.**(-2.)
        RHO(1)=1.5
        RHO(2)=1.5
        RHO(3)=1.5
        XI(1)=0.1
        XI(2)=0.1
        XI(3)=0.1
        XI(4)=0.1
      ELSE IF (ctr==5) THEN
        D=1000
        EPS(1)=5.*10.**(-3.)
        EPS(2)=5.*10.**(-2.)
        EPS(3)=17.*10.**(-2.)
        RHO(1)=1.5
        RHO(2)=1.5
        RHO(3)=1.5
        XI(1)=0.5
        XI(2)=0.1
        XI(3)=0.1
        XI(4)=0.5
      ELSE IF (ctr==6) THEN
        D=2000
        EPS(1)=7.*10.**(-3.)
        EPS(2)=8.*10.**(-2.)
        EPS(3)=3.*10.**(-1.)
C      NTB 2024:
C      RHO(1), RHO(2) and RHO(3) multiplied by a factor 0.8

```

```

C:\Temp\v2_Schubert_FORTTRAN_66_1972.f 5
      RHO(1)=0.8*1.5
      RHO(2)=0.8*1.5
      RHO(3)=0.8*1.3
      XI(1)=0.5
      XI(2)=0.1
      XI(3)=0.1
      XI(4)=0.5
      ELSE IF (ctr==7) THEN
        D=5000
        EPS(1)=10.**(-2.)
        EPS(2)=15.*10.**(-2.)
        EPS(3)=6.*10.**(-1.)
C      NTB 2024:
C      RHO(1), RHO(2) and RHO(3) multiplied by a factor 0.8
      RHO(1)=0.8*1.5
      RHO(2)=0.8*1.5
      RHO(3)=0.8*1.3
      XI(1)=0.3
      XI(2)=0.1
      XI(3)=0.1
      XI(4)=0.7
      ELSE
        PRINT *, 'D-loop complete: To exit, press <ENTER>'
        READ(*,*)
        STOP
      END IF

C      PRINT OUT INPUT PARAMETERS.

      WRITE(6,98) D,RHO,XI,EPS

C      COMPUTE PARAMETERS DEPENDENT ON THE INPUT PARAMETER D, INCLUDING
C      THE COEFFICIENTS, CO(I),I=1,...,NR, IN THE NUMERICAL INTEGRATION
C      FOR THE FLUX.

      DDRDAM=D*DRDAM
      DDR2=D*DR**2
      CON=4./(PI*D)
      CO(1)=16.*DELA(1)/(3.*PI*D)
      DO 105 I=2,NR
105 CO(I)=CON*DELA(I)

C      COMPUTE COMPLEMENTS (RELATIVE TO 1) OF SMOOTHING PARAMETERS AND
C      OVER-RELAXATION FACTORS.
C      ALSO COMPUTE SOR CONVERGENCE TOLERANCES, EPPS(I),I=1,2,3, AS
C      FUNCTIONS OF OUTER ITERATION TOLERANCES, EPS(I),I=1,2,3.

      DO 6 I=1,3
        XIC(I)=1.-XI(I)
        RHOC(I)=1.-RHO(I)
6 EPPS(I)=.05*EPS(I)
        XIC(4)=1.-XI(4)

```



```

C:\Temp\v2_Schubert_FORTRAN_66_1972.f 6
C      TEST WHETHER INITIAL OUTER ITERATES ARE TO BE OBTAINED FROM
C      MEMORY, HAVING BEEN PLACED THERE AS THE SOLUTION FOR A PREVIOUS
C      VALUE OF D BY A PREVIOUS COMPUTATION THIS RUN.

      IF(IUSE.EQ.0) GO TO 7
      DO 106 I=1,NRP1
      DO 106 J=1,NAP1
      PHI(I,J,3)=PHI(I,J,4)
      W(I,J,3)=W(I,J,4)
106  OMEGA(I,J,3)=OMEGA(I,J,4)
      WRITE(6,87) DSTART
      GO TO 9

C      INITIALIZE OUTER ITERATES TO ZERO IF NEITHER INPUT NOR COMPUTED
C      PREVIOUSLY THIS RUN.

      7 DO 8 I=1,NRP1
      DO 8 J=1,NAP1
      PHI(I,J,3)=0.
      W(I,J,3)=0.
      8 OMEGA(I,J,3)=0.

C      INITIALIZE OUTER ITERATION COUNTER (IOUT) AND COUNTERS OF NUMBER
C      OF OVER-RELAXATION FACTORS USED FOR W AND OMEGA (IRW,IRO, RESP.)
C      FOP THIS DATA CASE.

      9 IOUT=0
      IRW=0
      IRO=0

C      TEST FOR MAXIMUM NUMBER OF OUTER ITERATIONS.

10  IF(IOUT.GE.MAXOUT) GO TO 58

C      UPDATE OUTER ITERATION COUNTER, WRITE MESSAGE INDICATING NEW
C      OUTER ITERATION NUMBER, AND SET OUTER ITERATION CONVERGENCE
C      INDICATOR (ICV) TO ZERO. AFTER COMPUTATION OF ALL CURRENT OUTER
C      ITERATES AND COMPARISON WITH PREVIOUS OUTER ITERATES AGAINST THE
C      SPECIFIED TOLERANCES, ICV WILL STILL BE ZERO IF CONVERGENCE HAS
C      BEEN OBTAINED, OTHERWISE ICV WILL BE NON-ZERO.

      IOUT=IOUT+1
      WRITE(6,92) IOUT
      ICV=0

C      UPDATE PREVIOUS OUTER ITERATES.
      DO 12 I=1,NRP1
      DO 12 J=1,NAP1
      PHI(I,J,1)=PHI(I,J,3)
      W(I,J,1)=W(I,J,3)
12  OMEGA(I,J,1)=OMEGA(I,J,3)

C      COMPUTE CONSTANT SOR COEFFICIENT FOR PHI.

```

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7

```

      DO 13 I=2,NR
      DO 13 J=2,NA
13  C(I,J)=B(I,5)*OMEGA(I,J,1)

C      INITIALIZE SOR ITERATION COUNTER FOR PHI.

      ISOR=0

C      TEST FOR MAXIMUM NUMBER OF SOR ITERATIONS FOR PHI.

14  IF(ISOR.GE.MAXSOR) GO TO 55

C      UPDATE SOR ITERATION COUNTER IF MAXIMUM NUMBER HAS NOT BEEN
C      ACHIEVED.

      ISOR=ISOR+1

C      UPDATE PREVIOUS SOR ITERATES FOR PHI.

      DO 16 I=2,NR
      DO 16 J=2,NA
16  PHI(I,J,2)=PHI(I,J,3)

C      SET SOR ITERATION CONVERGENCE INDICATOR (ICONV) TO ZERO. AFTER
C      COMPUTATION OF CURRENT SOR ITERATE AND COMPARISON WITH PREVIOUS
C      ITERATE AGAINST THE TOLERANCE, ICONV WILL STILL BE ZERO IF
C      CONVERGENCE HAS BEEN OBTAINED. OTHERWISE IT WILL BE NON-ZERO.

      ICONV=0

C      COMPUTE CURRENT SOR ITERATE FOR PHI...
C      ...FIRST ON INTERIOR OF REGION, EXCLUDING 'INNER BOUNDARY'
C      R = 1.-DR.

      DO 18 I=2,NRM1
      DO 18 J=2,NA
          PHI(I,J,3)=RHOC(1)*PHI(I,J,2)+RHO(1)*(B(I,1)*PHI(I+1,J,2)
*      +B(I,2)*PHI(I,J+1,2)+B(I,3)*PHI(I-1,J,3)+B(I,4)*PHI(I,J-1,3)
*      +C(I,J))
          IF(ABS(PHI(I,J,2)-PHI(I,J,3)).GT.EPPS(1)) ICONV=1
18  CONTINUE

C      ...THEN ON 'INNER BOUNDARY' R = 1.-DR.

      DO 19 J=2,NA
          PHI(NR,J,3)=RHOC(1)*PHI(NR,J,2)+RHO(1)*.25*PHI(NRM1,J,3)
          IF(ABS(PHI(NR,J,2)-PHI(NR,J,3)).GT.EPPS(1)) ICONV=1
19  CONTINUE

C      TEST FOR CONVERGENCE OF SOR ITERATION FOR PHI.

      IF(ICONV.NE.0) GO TO 14

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C      SOR CONVERGENCE ATTAINED FOR PHI. SMOOTH OUTER ITERATE.
DO 20 I=2,NR
DO 20 J=2,NA
    PHI(I,J,3)=XI(1)*PHI(I,J,1)+XIC(1)*PHI(I,J,3)
    IF(ABS(PHI(I,J,1)-PHI(I,J,3)).GT.EPS(1)) ICV=1
20 CONTINUE

C      PRINT OUT SMOOTHED CURRENT OUTER ITERATE FOR PHI.

CALL OUTPUT('PHI ',ISOR,PHI(1,1,3))

C      COMPUTE COEFFICIENTS FOR SOR ITERATION FOR W...
C      ...FIRST COMPUTE COEFFICIENTS AT THE ORIGIN

E0=4.*ABS(PHI(2,NAH,3))
E1=(1.-AMIN1(PHI(2,NAH,3),0.))/E0
E2=2./E0
E3=(1.+AMAX1(PHI(2,NAH,3),0.))/E0
E4=DDR2/E0

C      ...NEXT COMPUTE COEFFICIENTS FOR REMAINDER OF REGION...
C      FIRST FOR RAYS ALONG ALPHA = 0 AND ALPHA = PI, EXCLUDING
C      R = 0 AND R = 1.

DO 23 I=2,NR
DELTA1=DA-PHI(I,2,3)
DELTA2=DA+PHI(I,NA,3)
EE(I)=2.*(DADR+DRDA*RINV2(I))
EE1=EE(I)+RINV(I)*ABS(DELTA1)
EE2=EE(I)+RINV(I)*ABS(DELTA2)
E(I,1,1)=(DADR+RINV(I)*AMAX1(DELTA1,0.))/EE1
E(I,NAP1,1)=(DADR+RINV(I)*AMAX1(DELTA2,0.))/EE2
EF(I)=DRDA*RINV2(I)
E(I,1,2)=EF(I)/EE1
E(I,NAP1,2)=EF(I)/EE2
E(I,1,3)=(DADR-RINV(I)*AMIN1(DELTA1,0.))/EE1
E(I,NAP1,3)=(DADR-RINV(I)*AMIN1(DELTA2,0.))/EE2
E(I,1,4)=E(I,1,2)
E(I,NAP1,4)=E(I,NAP1,2)
E(I,1,5)=DDRDM/EE1
23 E(I,NAP1,5)=DDRDM/EE2

C      THEN ON INTERIOR OF REGION.

DO 25 I=2,NR
DO 25 J=2,NA
    GAMMA=.5*(PHI(I+1,J,3)-PHI(I-1,J,3))
    DELTA=DA-.5*(PHI(I,J+1,3)-PHI(I,J-1,3))
    E(I,J,6)=EE(I)+RINV(I)*(ABS(GAMMA)+ABS(DELTA))
    E(I,J,1)=(DADR+RINV(I)*AMAX1(DELTA,0.))/E(I,J,6)
    E(I,J,2)=(EF(I)+RINV(I)*AMAX1(GAMMA,0.))/E(I,J,6)
    E(I,J,3)=(DADR-RINV(I)*AMIN1(DELTA,0.))/E(I,J,6)

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      E(I,J,4)=(EF(I)-RINV(I)*AMIN1(GAMMA,0.))/E(I,J,6)
25  E(I,J,5)=DDRDAM/E(I,J,6)

C      INITIALIZE SOR ITERATION COUNTER FOR W.

26  ISOR=0

C      TEST FOR MAXIMUM NUMBER OF SOR ITERATIONS.

27  IF(ISOR.GE.MAXSOR) GO TO 56

C      UPDATE SOR ITERATION COUNTER IF MAXIMUM HAS NOT BEEN ACHIEVED.

      ISOR=ISOR+1

C      UPDATE PREVIOUS SOR ITERATES FOR W...
C      ...FIRST AT THE ORIGIN

      W(1,1,2)=W(1,1,3)

C      ...THEN ON REMAINDER OF REGION EXCLUDING R = 1.

      DO 29 I=2,NR
      DO 29 J=1,NAP1
29  W(I,J,2)=W(I,J,3)

C      SET SOR CONVERGENCE INDICATOR (ICONV) TO ZERO.

      ICONV=0

C      COMPUTE CURRENT SOR ITERATE FOR W...
C      ...FIRST AT THE ORIGIN

      W(1,1,3)=RHOC(2)*W(1,1,2)+RHO(2)*(E1*W(2,1,2)+E2*W(2,NAH,2)
* +E3*W(2,NAP1,2)+E4)

C      (SET VALUES OF W FOR R = 0 AND ALL ANGLES ALPHA(I), I=1,...,NA+1,
C      EQUAL TO VALUE OF W AT ORIGIN FOR CONVENIENCE IN SOR COMPUTATION.)

      DO 30 J=2,NAP1
30  W(1,J,3)=W(1,1,3)
      IF(ABS(W(1,1,2)-W(1,1,3)).GT.EPPS(2)) ICONV=1

C      ...NEXT ALONG RAY ALPHA = 0. EXCLUDING R = 0 AND R = 1.

      DO 32 I=2,NR
      W(I,1,3)=RHOC(2)*W(I,1,2)+RHO(2)*(E(I,1,1)*W(I+1,1,2)+E(I,1,2)*2.*
* W(I,2,2)+E(I,1,3)*W(I-1,1,3)+E(I,1,5))
      IF(ABS(W(I,1,3)-W(I,1,2)).GT.EPPS(2)) ICONV=1
32  CONTINUE

C      ...NEXT ON INTERIOR OF REGION

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DO 33 I=2,NR
DO 33 J=2,NA
W(I,J,3)=RHOC(2)*W(I,J,2)+RHO(2)*(E(I,J,1)*W(I+1,J,2)+E(I,J,2)*
* W(I,J+1,2)+E(I,J,3)*W(I-1,J,3)+E(I,J,4)*W(I,J-1,3)+E(I,J,5))
IF(ABS(W(I,J,2)-W(I,J,3)).GT.EPPS(2)) ICONV=1
33 CONTINUE

C    ...FINALLY ALONG RAY ALPHA = PI. EXCLUDING R = 0 AND R = 1.

DO 34 I=2,NR
W(I,NAP1,3)=RHOC(2)*W(I,NAP1,2)+RHO(2)*(E(I,NAP1,1)*W(I+1,NAP1,2)+
* E(I,NAP1,3)*W(I-1,NAP1,3)+2.*E(I,NAP1,4)*W(I,NA,3)+E(I,NAP1,5))
IF(ABS(W(I,NAP1,2)-W(I,NAP1,3)).GT.EPPS(2)) ICONV=1
34 CONTINUE

C    TEST FOR CONVERGENCE OF SOR ITERATION FOR W.

IF(ICONV.NE.0) GO TO 27

C    SOR CONVERGENCE ATTAINED FOR W. SMOOTH OUTER ITERATE...
C    ...FIRST AT THE ORIGIN

W(1,1,3)=XI(2)*W(1,1,1)+XIC(2)*W(1,1,3)

C    (SET VALUES OF W FOR R = 0 AND ALL DISCRETE ANGLES EQUAL TO
C    SMOOTHED VALUE OF W AT ORIGIN.)

DO 134 J=2,NAP1
134 W(1,J,3)=W(1,1,3)
IF(ABS(W(1,1,1)-W(1,J,3)).GT.EPS(2)) ICV=1

C    ...THEN ON REMAINDER OF REGION, EXCLUDING R = 1.

DO 35 I=2,NR
DO 35 J=I,NAP1
W(I,J,3)=XI(2)*W(I,J,1)+XIC(2)*W(I,J,3)
IF(ABS(W(I,J,1)-W(I,J,3)).GT.EPS(2)) ICV=1
35 CONTINUE

C    PRINT OUT SMOOTHED CURRENT OUTER ITERATE FOR W.

CALL OUTPUT('W ',ISOR,W(1,1,3))

C    COMPUTE AND SMOOTH OMEGA ON BOUNDARY R = 1.

DO 37 J=2,NA
OMEGA(NRP1,J,3)=XI(3)*OMEGA(NRP1,J,1)-XIC(3)*2.*RINV2(2)*PHI(NR,
* J,3)
IF(ABS(OMEGA(NRP1,J,1)-OMEGA(NRP1,J,3)).GT.EPS(3)) ICV=1
37 CONTINUE

C    COMPUTE CONSTANT COEFFICIENT FOR SOR ITERATION FOR OMEGA.

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      DO 40 I=2,NR
      DO 40 J=2,NA
40    E(I,J,6)=-W(I,J,3)*(SA(J)*(W(I+1,J,3)-W(I-1,J,3))+CA(I,J)*(W(I,
      * J+1,3)-W(I,J-1,3)))/E(I,J,6)

C      INITIALIZE COUNTER OF SOR ITERATION NUMBER FOR OMEGA.

41    ISOR=0

C      TEST FOR MAXIMUM NUMBER OF SOR ITERATIONS.

42    IF(ISOR.GE.MAXSOR) GO TO 57

C      UPDATE SOR ITERATION COUNTER IF MAXIMUM NUMBER HAS NOT BEEN
C      ACHIEVED.

      ISOR=ISOR+1

C      UPDATE PREVIOUS SOR ITERATES FOR OMEGA ON INTERIOR.

      DO 44 I=2,NR
      DO 44 J=2,NA
44    OMEGA(I,J,2)=OMEGA(I,J,3)

C      SET SOR CONVERGENCE INDICATOR TO ZERO.

      ICONV=0

C      COMPUTE CURRENT SOR ITERATE FOR OMEGA ON INTERIOR.

      DO 46 I=2,NR
      DO 46 J=2,NA
      OMEGA(I,J,3)=RHOC(3)*OMEGA(I,J,2)+RHO(3)*(E(I,J,1)*OMEGA(I+1,J,2)
      * +E(I,J,2)*OMEGA(I,J+1,2)+E(I,J,3)*OMEGA(I-1,J,3)+E(I,J,4)
      * *OMEGA(I,J-1,3)+E(I,J,6))
      IF(ABS(OMEGA(I,J,2)-OMEGA(I,J,3)).GT.EPPS(3)) ICONV=1
46    CONTINUE

C      TEST FOR CONVERGENCE OF SOR ITERATION FOR OMEGA.

      IF(ICONV.NE.0) GO TO 42

C      SOR CONVERGENCE ATTAINED FOR OMEGA. SMOOTH OUTER ITERATE.

      DO 48 I=2,NR
      DO 48 J=2,NA
      OMEGA(I,J,3)=XI(4)*OMEGA(I,J,1)+XIC(4)*OMEGA(I,J,3)
      IF(ABS(OMEGA(I,J,1)-OMEGA(I,J,3)).GT.EPS(3)) ICV=1
48    CONTINUE

C      PRINT OUT SMOOTHED CURRENT OUTER ITERATE FOR OMEGA.

      CALL OUTPUT('OMEGA', ISOR, OMEGA(1,1,3))

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C      TEST FOR CONVERGENCE OF ALL OUTER ITERATES.

      IF(ICV.NE.0) GO TO 10

C      PRINT MESSAGE INDICATING CONVERGENCE OF OUTER ITERATION.

      WRITE(6,97)

C      COMPUTE RATIO OF FLUX IN CURVED TUBE TO THAT IN STRAIGHT TUBE.

      QR=0.
      DO 49 J=1,NA
49  QR=QR+W(1,J,3)+W(2,J,3)+W(2,J+1,3)
      QR=QR*CO(1)
      DO 249 I=2,NR
      S=0.
      DO 149 J=1,NA
149  S=S+W(I,J,3)+W(I+1,J,3)+W(I,J+1,3)+W(I+1,J+1,3)
249  QR=QR+CO(I)*S
C      PRINT OUT VALUE OF FLUX RATIO JUST COMPUTED.

      WRITE(6,90) QR

C      WRITE SOLUTION TO FILE IF INPUT CONTROL
C      PARAMETER IPCH SO DICTATES, AND PRINT MESSAGE INDICATING THAT
C      THIS FILE WRITING WAS DONE.

C      NTB 2024:
C      Write solution to file
      IF (IPCH.NE.0) THEN
        WRITE(file_id, '(i0)') INT(D)
        file_name = 'file_D' // TRIM(ADJUSTL(file_id)) // '.dat'
        PRINT*, "file name is ", file_name
        OPEN(1, FILE = file_name, STATUS = 'replace', RECL = 600000)
        WRITE(1,*) NRP1
        WRITE(1,*) NAP1
        WRITE(1,*) XI
        WRITE(1,*) RHO
        WRITE(1,*) EPS
        WRITE(1,*) D
        WRITE(1,*) QR
        DO 350 I=1,NRP1
350  WRITE(1,*) PHI(I,:,3)
        DO 360 I=1,NRP1
360  WRITE(1,*) W(I,:,3)
        DO 370 I=1,NRP1
370  WRITE(1,*) OMEGA(I,:,3)
        CLOSE(1)
      END IF

      IF(IPCH.NE.0) WRITE(6,86)

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C      TEST WHETHER OR NOT SOLUTION JUST OBTAINED IS TO BE SAVED IN
C      MEMORY FOR SOME SUCCEEDING CASE WITH A DIFFERENT VALUE OF D.

      IF(ISAVE.EQ.0) GO TO 5

C      SAVE CURRENT SOLUTION IN ANOTHER AREA OF MEMORY.

      DO 50 I=1,NRP1
      DO 50 J=1,NAP1
      PHI(I,J,4)=PHI(I,J,3)
      W(I,J,4)=W(I,J,3)
50    OMEGA(I,J,4)=OMEGA(I,J,3)

C      SAVE VALUE OF D FOR WHICH SOLUTION WAS JUST OBTAINED IN DSTART.

      DSTART=D
      GO TO 5

C      CONVERGENCE FAILURE MESSAGES

C      PHI ITERATION FAILED. READ NEXT DATA CASE.

55    WRITE(6,96)
      GO TO 5

C      W ITERATION FAILED. REDUCE OVER-RELAXATION FACTOR AND TRY AGAIN,
C      UNLESS THIS HAS ALREADY BEEN DONE THE MAXIMUM NUMBER OF TIMES
C      (NOR), IN WHICH CASE READ NEXT DATA CASE.

56    WRITE(6,95) RHO(2)
      IF(IRW.GE.NOR) GO TO 5
      IRW=IRW+1
      RHO(2)=RHO(2)-DOR(IRW)
      RHOC(2)=1.-RHO(2)
      DO 156 I=1,NRP1
      DO 156 J=1,NAP1
156    W(I,J,3)=W(I,J,1)
      GO TO 26

C      OMEGA ITERATION FAILED. REDUCE O-R FACTOR AND TRY AGAIN, UNLESS
C      THIS HAS ALREADY BEEN DONE THE MAXIMUM NUMBER OF TIMES (NOR),
C      IN WHICH CASE READ THE NEXT DATA CASE.

57    WRITE(6,94) RHO(3)
      IF(IRO.GE.NOR) GO TO 5
      IRO=IRO+1
      RHO(3)=RHO(3)-DOR(IRO)
      RHOC(3)=1.-RHO(3)
      DO 157 I=1,NRP1
      DO 157 J=1,NAP1
157    OMEGA(I,J,3)=OMEGA(I,J,1)
      GO TO 41

```



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C      OUTER ITERATION FAILED. PRINT MESSAGE INDICATING THIS AND READ
C      NEXT DATA CASE.

58 WRITE(6,93)
   GO TO 5

C      TERMINATION POINT FOR PROGRAM. CONTROL REACHES HERE AFTER ATTEMPT
C      TO READ PAST LAST DATA RECORD.

70 STOP

98 FORMAT(6X 'D =' F5.0//13X 'PHI' 7X 'W' 5X 'OMEGA' // 5X
* 'RHO =' F6.2,2(3X F6.2)/6X 'XI =' F6.4,3(3X F6.4)/5X 'EPS ='
* F6.5,2(3X F6.5))
97 FORMAT('OUTER ITERATION CONVERGED TO GIVEN TOLERANCES.')
96 FORMAT('SOR FOR PHI FAILED.')
95 FORMAT('SOR FOR W FAILED WITH SOR FACTOR =' F6.2)
94 FORMAT('SOR FOR OMEGA FAILED WITH SOR FACTOR =' F6.2)
93 FORMAT('OUTER ITERATION FAILED TO CONVERGE.')
92 FORMAT(// 'OUTER ITERATION' I5//)
90 FORMAT('FLUX RATIO =' F10.5)
87 FORMAT('INITIAL ITERATE TAKEN FROM SOLUTION FOR D =' F7.0)
86 FORMAT('SOLUTION WAS OUTPUT TO FILE.')

END

C      THIS ROUTINE PRINTS OUT A DISCRETE FUNCTION IN A RECTANGULAR
C      FORMAT WHICH IS RELATED TN THE FOLLOWING WAY TO THE POLAR GRID
C      IMPOSED ON THE PHYSICAL REGION.
C      THE TOP LINE OF THE PRINT BLOCK CORRESPONDS TO VALUES OF THE
C      FUNCTION ALONG THE ARC R = 1.
C      THE BOTTOM LINE OF THE PRINT BLOCK CORRESPONDS TO THE VALUE
C      OF THE FUNCTION AT THE ORIGIN (R = 0).

SUBROUTINE OUTPUT(VAR,ISOR,A)
PARAMETER NR=10,NA=18,NRP1=NR+1,NAP1=NA+1
DIMENSION A(NRP1,NAP1)

C      NTB 2024:
C      Added definitions
CHARACTER*5 APhi, AW, AOMEGA, VAR

DATA APhi /'PHI'/, AW /'W', AOMEGA /'OMEGA'/
99 FORMAT(A6,5X I5,2X 'SOR ITERATIONS'/)
98 FORMAT(1X F6.2,17F7.2,F6.2)
97 FORMAT(1X F6.1,17F7.1,F6.1)
KRP1=NRP1
KAP1=NAP1
WRITE(6,99) VAR,ISOR
IF(VAR.NE.APhi) GO TO 8
DO 5 I=1,NRP1
5 WRITE(6,98) (A(KRP1-I+1,KAP1-J+1),J=1,KAP1)
RETURN

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```
8 DO 10 I=1,NRP1  
10 WRITE(6,97) (A(KRP1-I+1,KAP1-J+1),J=1,KAP1)  
RETURN  
END
```

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