TEKNISK RAPPORT 177/88

FUGTTRANSPORT BESKREVET SOM ENDIMENSIONAL LINEÆR DIFFUSION

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FORORD

Ved Laboratoriet for Bygningsmaterialer indgår emnet fugtbinding og fugtvandring i bygningsmaterialer i det langsigtede forskningsprogram.

Den foreliggende rapport omhandler fugttransport i porøse bygningsmaterialer under isoterme forhold beskrevet ved lineær diffusionsteori. Rapporten giver et basisgrundlag for de fugtvandringsberegninger, der opstilles senere i projektet.

Arbejdet er udført som led i FTU-projektet "Fugt i byggematerialer" (J.nr. 5.17.3.6.13), som udføres ved Laboratoriet for Bygningsmaterialer i perioden 1987-89.

Anders Nielsen
Projektleder

INDHOLDSFORTEGNELSE

1. SAMMENFATNING

Denne rapport omhandler fugttransport i porøse bygningsmaterialer under isoterme forhold beskrevet ved lineær diffusionsteori. Det skal fra starten slås fast, at det oftest er en stor forenkling af virkeligheden at beskrive fugttransport i porøse bygningsmaterialer som lineær diffusion. Lineær diffusionsteori kan dog være et godt hjælpeværktøj til at bestemme størrelsesordenen af fugttransporten.

Rapporten beskriver tre klassiske analytiske løsninger til den lineære endimensionale diffusionsligning, nemlig plade-, cylinder- og kugletilfældet med konstant vandindhold i overfladen og konstante vandindhold til tidspunkterne $t = 0$ og $t \rightarrow \infty$.

Da de analytiske løsninger numerisk set kan være vanskelige at evaluere, er der fremstillet EDB-programmerne CYLDIF og CARDIF, der løser den endimensionale lineære diffusionsligning numerisk ved hjælp af endelige differensers metode i henholdsvis cylinderkoordinater, kartesiske og kuglekoordinater. Numerisk løsning har endvidere den fordel, at diffusionsligningen kan løses for næsten vilkårlige rand- og begyndelsesbetingelser.

Løsningerne til diffusionsligningen i de tre tilfælde beskrives i form af kurver og tabeller. Kurverne er fugtprofiler optegnet for en række Fourier-tal.

Endelig er der udarbejdet analytiske beskrivelser af middelfugtindholdet i de tre behandlede geometrier som funktion af Fourier-tallet.

2. DEN ENDIMENSIONALE LINEÆRE DIFFUSIONSLIGNING

2.1 Opstilling af den endimensionale lineære diffusionsligning

Diffusion af f.eks. vanddamp i porøse bygningsmaterialer eller af atomer i metaller kan beskrives ved hjælp af Ficks 1. lov som

$$J = -D \frac{\partial c}{\partial x} \qquad (2.1)$$

hvor

J = flux af det, som diffunderer
D = diffusivitet
c = koncentrationen af det, som diffunderer
x = stedkoordinaten

Opstilles kontinuitetsligningen for det i figur 1 viste kontrolvolumen, fås jvf. Crank /1/

$$\text{fraført} - \text{tilført} + \text{oplagret} = 0 \quad \Leftrightarrow$$

$$\left(J + \frac{\partial J}{\partial x}dx\right)dy\,dz - J\,dy\,dz + \frac{\partial c}{\partial t}dx\,dy\,dz = 0 \quad \Leftrightarrow$$

$$\frac{\partial J}{\partial x}dx\,dy\,dz + \frac{\partial c}{\partial t}dx\,dy\,dz = 0 \quad \Leftrightarrow$$

$$\frac{\partial J}{\partial x} + \frac{\partial c}{\partial t} = 0 \tag{2.2}$$

Indsættes 2.1 i 2.2, fås den endimensionale ulineære partielle differentialligning

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \tag{2.3}$$

Regnes D for uafhængig af c, fås den tilsvarende lineære ligning

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \tag{2.4}$$

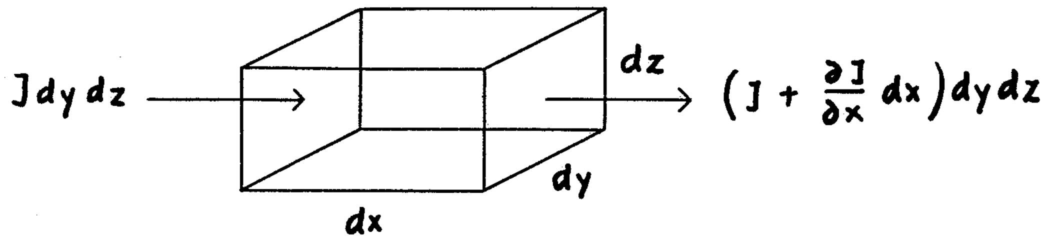
Opstilles 2.4 i cylinderkoordinater for endimensional symmetrisk diffusion i en cylinder, fås

$$\frac{\partial c}{\partial t} = D\left(\frac{1}{r}\frac{\partial c}{\partial r} + \frac{\partial^2 c}{\partial r^2}\right) \tag{2.5}$$

hvor r er den radiære stedkoordinat.

Opstilles 2.4 for endimensional symmetrisk diffusion i en kugle, fås ligningen

$$\frac{\partial c}{\partial t} = D\left(\frac{2}{r}\frac{\partial c}{\partial r} + \frac{\partial^2 c}{\partial r^2}\right) \tag{2.6}$$



Figur 1. Kontrolvolumen. Planparallelt tilfælde.

2.2 Analytisk løsning af den endimensionale lineære diffusionsligning

Ligningerne 2.4, 2.5 og 2.6 kan kun løses analytisk i få tilfælde og da kun for specielle rand- og begyndelsesbetingelser. I det følgende gennemgås løsninger til 2.4, 2.5 og 2.6, hvor der som drivende potentiale er anvendt vandindholdet u_∞ i et porøst bygningsmateriale. Løsningerne er givet for randbetingelsen konstant vandindhold u_∞ i overfladen og begyndelsesbetingelsen et jævnt fordelt vandindhold u_o gennem hele materialet. Løsninger findes f.eks. i Crank /1/ og er opnået ved separation af de variable (f.eks. gennemgået i /2/).

Der forudsættes i det følgende altså begyndelsesbetingelsen (BB)

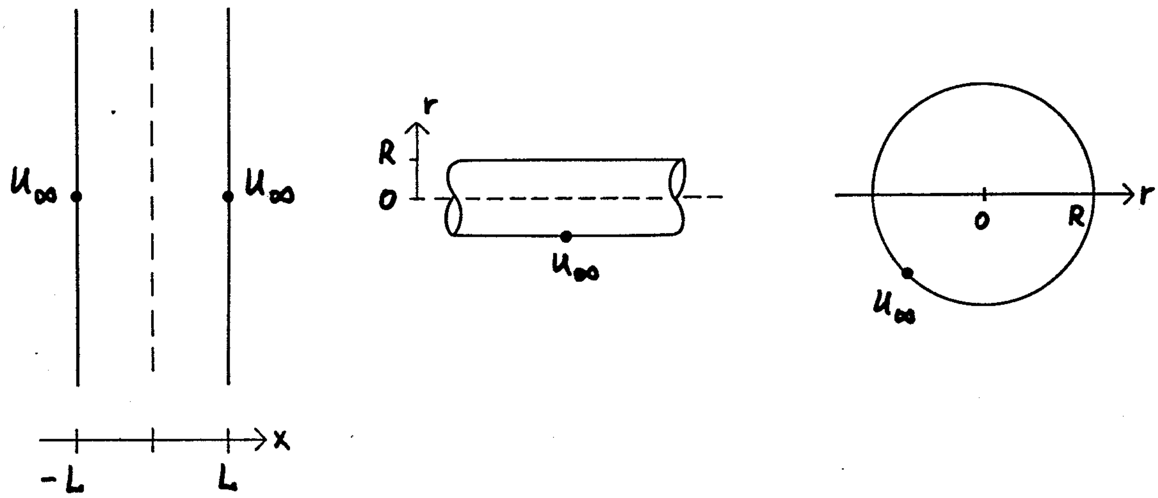
$$u(r,t) = u_o \quad , \quad t < 0$$

og randbetingelsen (RB)

$$u(R,t) = u_\infty \quad , \quad t \geq 0$$

idet

r = stedkoordinat [m]
t = tiden [s]
R = karakteristisk dimension for det betragtede legeme [m]



Figur 2. De anvendte betegnelser i plade-, cylinder- og kugletilfældet.

<u>Pladetilfældet</u>

$$\frac{u(r,t) - u_\infty}{u_0 - u_\infty} =$$

$$- \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{(2n-1)} e^{-[(2n-1)\pi/(2L)]^2 Dt}$$

$$\cdot \cos\left(\frac{2n-1}{2L} \pi x\right) \qquad (2.7)$$

Cylindertilfældet

$$\frac{u(r,t) - u_\infty}{u_o - u_\infty} =$$

$$2 \sum_{n=1}^{\infty} \frac{1}{\beta_n} e^{-(\beta_n/R)^2 Dt} \frac{J_o[\beta_n(r/R)]}{J_1(\beta_n)} \quad (2.8)$$

J_o = Besselfunktionen af 0. orden 1. art

J_1 = Besselfunktionen af 1. orden 1. art

β_n = den n'te rod af J_o, altså β_n er givet ved ligningen $J_o(\beta_n)$ = 0

Kugletilfældet

$$\frac{u(r,t) - u_\infty}{u_o - u_\infty} =$$

$$\frac{2R}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 Dt} \sin\left(\frac{n\pi r}{R}\right) \quad (2.9)$$

2.3 Numerisk løsning af den endimensionale lineære diffusionsligning

Da de analytiske løsninger numerisk set kan være vanskelige at evaluere, er der fremstillet EDB-programmerne CYLDIF og CARDIF, der løser den endimensionale lineære diffusionsligning numerisk ved hjælp af endelige differensers metode i henholdsvis cylinderkoordinater, kartesiske og kuglekoordinater. Numerisk løsningen har endvidere den fordel, at diffusionsligningen kan løses for næsten vilkårlige rand- og begyndelsesbetingelser.

2.3.1 Cylindertilfældet

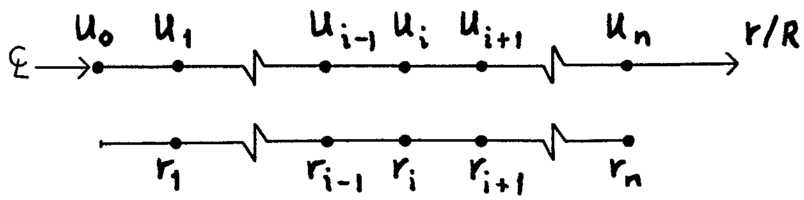
Til den numeriske løsning af ligning 2.5 er anvendt en eksplicit endelige differensers metode som beskrevet i f.eks. /3/. Metoden er, at vandindholdet i cylinderen beregnes i et endeligt antal punkter n i cylinderens radius, som det er vist i figur 3. Der er anvendt et fast stedsskridt i beregningerne nemlig

$$\Delta r = 1/n$$

Afstanden fra centrum af cylinderen til de enkelte punkter på cylinderens radius er

$$r_i = i(1/n)$$

hvor r_i er afstanden fra centrum til det i'te punkt. Det bemærkes, at $r_o = 0$ og $r_n = 1$, altså at r_i betegner en dimensionsløs radius.



Figur 3. Netinddeling i cylinderen.

De partielle afledede i ligning 2.5 erstattes med endelige differenstilnærmelser, og man får

$$\frac{u_i^{t_1+\Delta t} - u_i^{t_1}}{\Delta t} = D\left(\frac{1}{r_i} \frac{u_{i+1}^{t_1} - u_{i-1}^{t_1}}{2\Delta r} + \frac{u_{i+1}^{t_1} + u_{i-1}^{t_1} - 2u_i^{t_1}}{(\Delta r)^2} \right) \qquad (2.10)$$

hvor

$u_i^{t_1}$ = vandindhold i cylinderen i cirklen med radius r_i til tidspunktet $t = t_1$

Δt = tidsskridt

Vandindholdet i det i'te netpunkt på tidsniveauet $t = t_1 + \Delta t$, $u_i^{t_1+\Delta t}$, beregnes altså ud fra vandindholdet i selve punktet og de to omkringliggende punkter på tidsniveauet $t = t_1$.

Værdien af u_o, u_1, ..., u_n til tidspunktet t = 0 angiver begyndelsesbetingelsen ved den numeriske løsning af den partielle differentialligning (begyndelsesvandindholdet i konstruktionen). Værdien af u_n (konstant eller varierende som funktion af tiden) for $t \geq \Delta t$ angiver randbetingelsen til den numeriske løsning af den partielle differentialligning 2.5.

Der er et problem ved bestemmelse af u_o, d.v.s. af vandindholdet i cylinderens centrum, idet r_i i differensligningen 2.10 da bliver r_o = 0, og $1/r_o$ bliver udefineret. Det er dog muligt at bestemme u_o eksplicit, hvilket bliver vist i bilag 1 ved et ræsonnement, som bygger på analogien diffusion af temperatur i en cylinder. Her skal blot anføres resultatet

$$u_0^{t_1+\Delta t} = u_0^{t_1} - \frac{4D\Delta t}{(\Delta r)^2}\left(u_0^{t_1} + \left(\frac{2}{\ln 2} - 4\right)u_1^{t_1} + \left(3 - \frac{2}{\ln 2}\right)u_2^{t_1}\right) \quad (2.11)$$

For den eksplicitte formulering af endelige differensers metode gælder det, at der er grænser for, hvor store tidsskridt Δt man kan anvende i beregningerne, eller med andre ord hvor "hurtigt" man kan regne frem i tiden. Det vil ikke blive vist her, hvordan det maksimale Δt bestemmes (en metode til bestemmelse af det maksimale Δt, hvor den numeriske metode er stabil, kan findes i /5/, p. 17), men blive anført, at for differensligningen 2.10 er stabilitetskravet

$$1 - \frac{2D\Delta t}{(\Delta r)^2} > 0 \quad (2.12)$$

og for 2.11 er stabilitetskravet

$$1 - \frac{4D\Delta t}{(\Delta r)^2} > 0 \quad (2.13)$$

2.13 er det skrappeste af de to stabilitetskrav, og det bliver derfor det gældende.

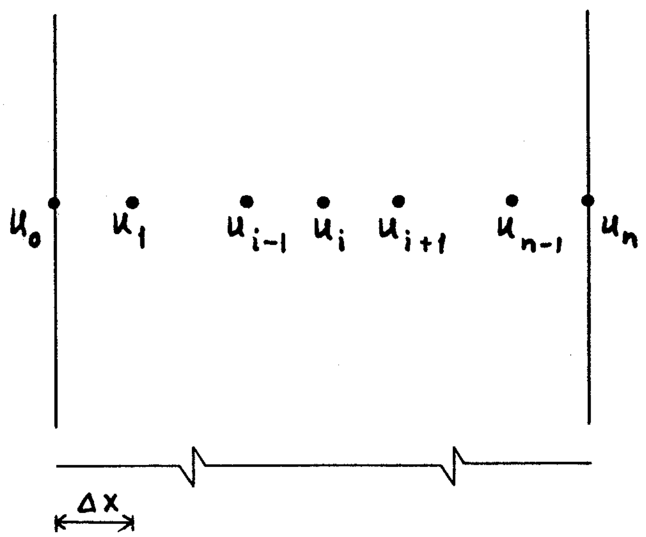
Den numeriske metode er implementeret i programmet CYLDIF. Programmet er listet i bilag 2. Den numeriske metode er kontrolleret ved sammenligning med den analytiske løsning (2.8), kontrollen er anbragt som bilag 3. Kontrollen viser, at implementeringen af den numeriske metode er i orden.

2.3.2 Pladetilfældet

Til den numeriske løsning af ligning 2.4 er anvendt en implicit endelige differensers metode som beskrevet i f.eks. /1/, /3/, /4/ og /5/. Metoden er, at vandindholdet i pladen beregnes i et endeligt antal punkter n i pladens tværsnit, som det er vist i figur 4. Der er anvendt et fast stedsskridt i beregningerne, nemlig x = 1/n.

Der er anvendt Crank-Nicolsons implicitte metode, der anvendt på ligning 2.4 giver differensligningen

$$\frac{u_i^{t_1+\Delta t} - u_i^{t_1}}{\Delta t} = \frac{D}{2(\Delta x)^2}\Big[u_{i-1}^{t_1+\Delta t} - 2u_i^{t_1+\Delta t} + u_{i+1}^{t_1+\Delta t} + u_{i-1}^{t_1} - 2u_i^{t_1} + u_{i+1}^{t_1}\Big] \qquad (2.14)$$



Figur 4. Netinddeling af plade.

Indsættes $R = \Delta tD/(\Delta x)^2$ i 2.14 og leddene omarrangeres, fås

$$-Ru_{i-1}^{t_1+\Delta t} + (2R+2)u_i^{t_1+\Delta t} - Ru_{i+1}^{t_1+\Delta t} =$$

$$Ru_{i-1}^{t_1} + (2-2R)u_i^{t_1} + Ru_i^{t_1} \qquad (2.15)$$

Af 2.15 ses det, at vandindholdet i det i'te netpunkt på tidsniveauet $t = t_1 + \Delta t$, $u_i^{t_1+\Delta t}$, beregnes altså ud fra vandindholdet i selve punktet og de to omkringliggende punkter på tidsniveauet $t = t_1$, samt de to omkringliggende punkters vandindhold på tidsniveauet $t = t_1 + \Delta t$.

Idet u_o og u_n i figur 4 angiver randbetingelserne, kan 2.15 opstilles for punkterne u_1, u_2, ..., u_{n-1}. I matrixformulering fås da ligningssystemet

$$\begin{bmatrix} (2R+2) & (-R) & & & \\ (-R) & (2R+2) & (-R) & & \\ & \ddots & \ddots & \ddots & \\ & & (-R) & (2R+2) & (-R) \\ & & & (-R) & (2R+2) \end{bmatrix} \begin{bmatrix} u_1^{t_1+\Delta t} \\ u_2^{t_1+\Delta t} \\ \vdots \\ u_{n-2}^{t_1+\Delta t} \\ u_{n-1}^{t_1+\Delta t} \end{bmatrix} =$$

$$\begin{bmatrix} Ru_0^{t_1+\Delta t} + Ru_0^{t_1} + (2-2R)u_1^{t_1} + Ru_2^{t_1} \\ Ru_1^{t_1} + (2-2R)u_2^{t_1} + Ru_3^{t_1} \\ \vdots \\ Ru_{n-3}^{t_1} + (2-2R)u_{n-2}^{t_1} + Ru_{n-1}^{t_1} \\ Ru_{n-2}^{t_1} + (2-2R)u_{n-1}^{t_1} + Ru_n^{t_1} + Ru_n^{t_1+\Delta t} \end{bmatrix} \qquad (2.16)$$

Vandindholdet i punkterne $u_1 - u_{n-1}$ på tidsniveauet $t_1 + \Delta t$ bestemmes altså ved løsning af ligningssystemet 2.16. Da koefficientmatricen på venstresiden af 2.16 er en tridiagonalmatrix, kan ligning 2.16 løses ved hjælp af en specielt simpel algoritme kaldet tridiagonalgoritme eller Thomas' algoritme (beskrevet i /4/ og /6/). Da koefficientmatricen på venstresiden af

2.16 endvidere er konstant, bliver algoritmen til ligningsløsningen yderligere simpel.

For den implicitte metode kan det vises, at den er ubetinget stabil for enhver størrelse af tidsskridtet Δt (se /4/ og /5/).

Den numeriske metode er implementeret i programmet CARDIF. Programmet er listet i bilag 4. Den numeriske metode er kontrolleret ved sammenligning med tabel 2.4 givet i /5/. Kontrollen er listet i bilag 5. Da tabellen i bilag 5 viser overensstemmelse med tabel 2.4 i /5/, er den numeriske metode implementeret tilfredsstillende.

2.3.3 Kugletilfældet

Det kan vises, at ligningen jvf. 2.6

$$\frac{\partial u}{\partial t} = D\left(\frac{2}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2}\right) \qquad (2.6')$$

ved transformationen w = ur kan føres over i

$$\frac{\partial w}{\partial t} = D\frac{\partial^2 w}{\partial r^2} \qquad (2.4')$$

hvilket er ligningen for pladetilfældet. Transformationen er vist i bilag 6.

Altså fås den numeriske løsning til 2.6' ud fra den numeriske løsning til 2.4', idet

$$u = \frac{r}{w} \quad \text{for} \quad w \neq 0$$

Den numeriske løsning til 2.6' fås altså ved hjælp af programmet CARDIF.

2.4 Middelvandindhold

Ønsker man at beregne middelvandindholdet i en konstruktion, er det bekvemt at have analytiske udtryk for dette. For de i dette notat 3 behandlede tilfælde plade-, cylinder- og kugletilfælde er der i dette afsnit angivet de analytiske udtryk for middelvandindholdet.

2.4.1 Middelvandindhold i pladetilfældet

Middelvandindholdet $u_m(t)$ er i pladetilfældet givet ved udtrykket

$$\frac{u_m(t) - u_\infty}{u_0 - u_\infty} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} e^{-[(2n-1)\pi/(2L)]^2 Dt} \qquad (2.17)$$

2.17 er udledt i bilag 7.

2.4.2 Middelvandindhold i cylindertilfældet

Middelvandindholdet $u_m(t)$ er i cylindertilfældet givet ved udtrykket

$$\frac{u_m(t) - u_\infty}{u_0 - u_\infty} = 4 \sum_{n=1}^{\infty} \frac{e^{-(\beta_n/R)^2 Dt}}{\beta_n^2} \qquad (2.18)$$

2.18 er udledt i bilag 8.

2.4.3 Middelvandindhold i kugletilfældet

Middelvandindholdet $u_m(t)$ er i kugletilfældet givet ved udtrykket

$$\frac{u_m(t) - u_\infty}{u_0 - u_\infty} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/R)^2 Dt} \qquad (2.19)$$

2.19 er udledt i bilag 9.

2.4.4 Program MEANMOIS til beregning af middelvandindhold

Til beregning af middelvandindholdet i de tre tilfælde givet ved ligningerne 2.17, 2.18 og 2.19 er udviklet programmet MEANMOIS. Programmet er listet i bilag 10. MEANMOIS beregner middelvandindholdet for et givet antal Fourier-tal, hvor Fourier-tallet Fo er givet ved

$$Fo = Dt/\delta^2$$

hvor δ er en karakteristisk længde, nemlig den halve bredde L i pladetilfældet, og radius R i cylinder- og kugletilfældet.

MEANMOIS bruger rødderne $ß_n$ af Bessel funktionen J_o af 0. orden 1. art til beregning af middelvandindholdet i cylindertilfældet. For små Fo-tal skal der medtages flere led i rækkeudviklingen end der normalt er angivet rødder $ß_n$ i litteraturen. Det har derfor været nødvendigt at beregne flere rødder til $ß_n$. Beregningsmetode og resultat er beskrevet i bilag 11.

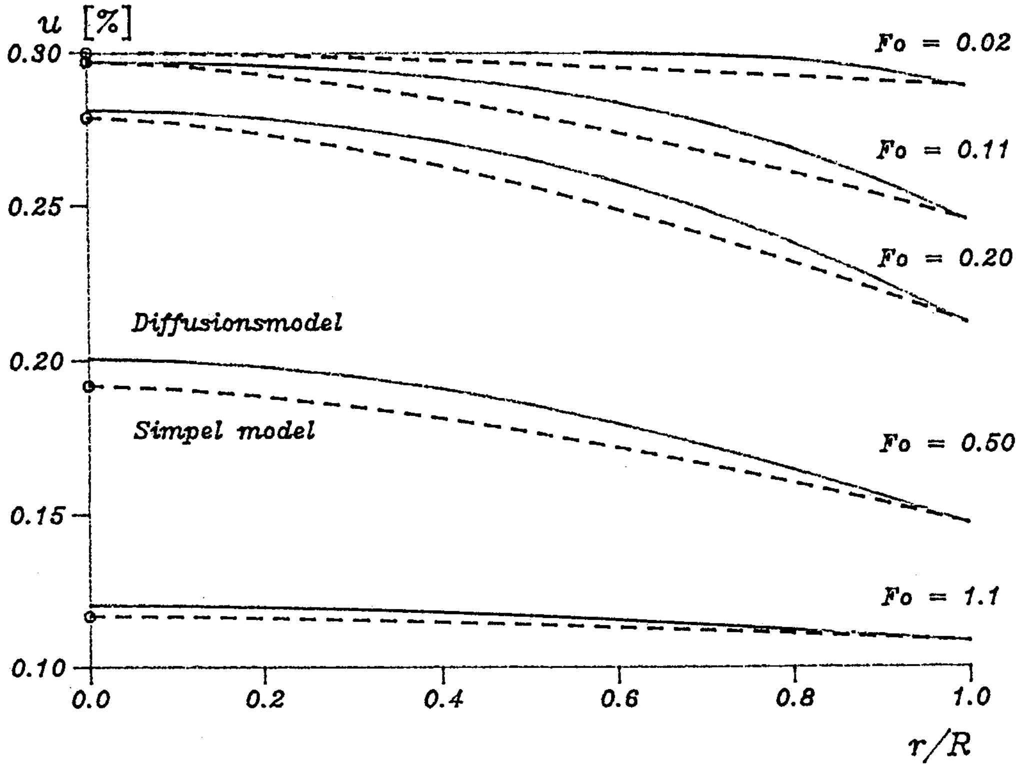
En udskrift fra en kørsel med MEANMOIS er anbragt som bilag 12.

3. KØRSLER MED DE UDVIKLEDE EDB-PROGRAMMER

I dette afsnit beskrives uddata fra EDB-programmerne CYLDIF, CARDIF og MEANMOIS kort.

3.1 Uddata fra CYLDIF

Programmet CYLDIF er benyttet ved udarbejdelsen af rapporten /7/. Fra denne er figur 5 hentet, der er fremstillet ved hjælp af uddata fra CYLDIF. De fuldt optrukne linier er fugtprofiler beregnet ved hjælp af CYLDIF. Der er her specificeret et eksponentielt aftagende fugtindhold i cylinderens overflade som randbetingelse. Cylinderen kan f.eks. være en træmast under udtørring.



Figur 5. Sammenligning af fugtprofiler beregnet ved forskellige metoder, fra /7/.

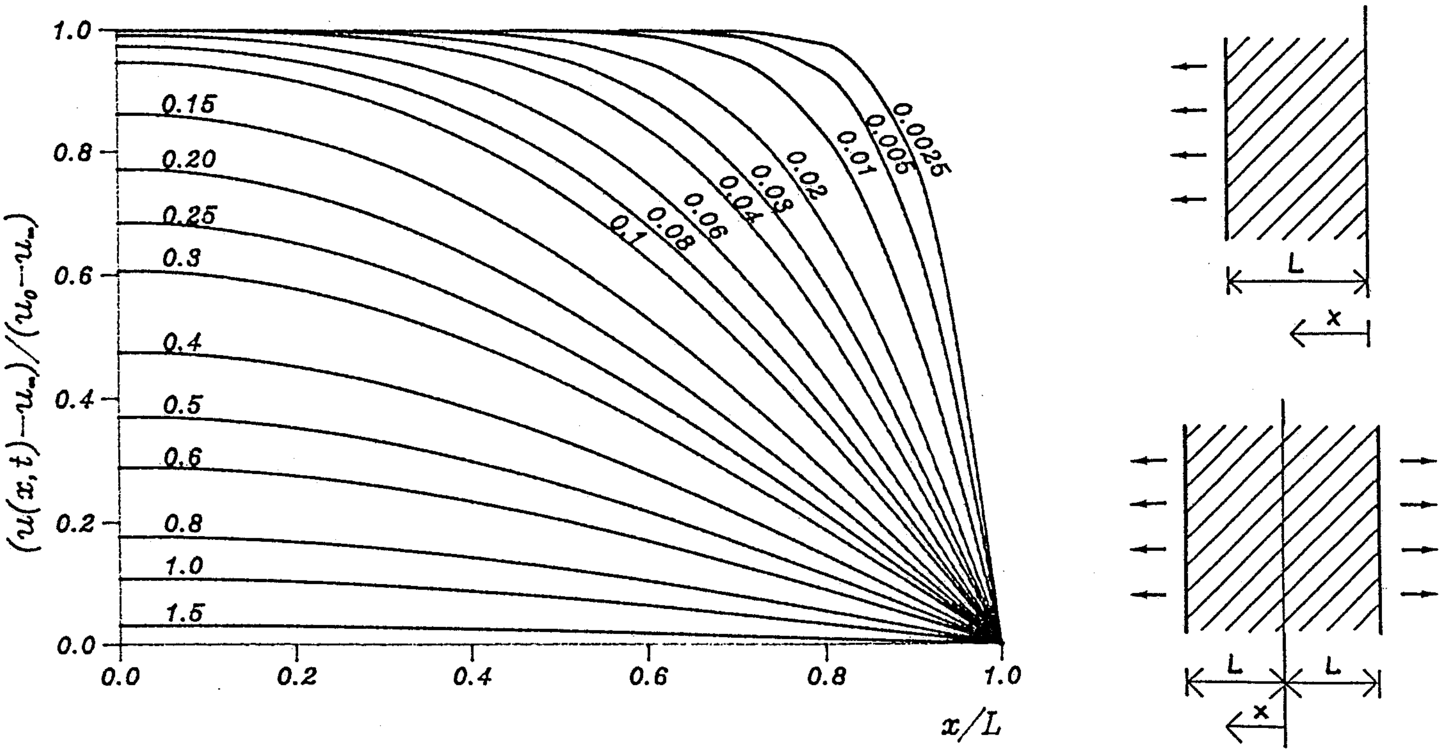
3.2 Uddata fra CARDIF

Uddata fra CARDIF foreligger dels i tabelform og dels i form af kurver. I figur 6 er vist et diagram, hvor man ved hjælp af to dimensionsløse størrelser kan bestemme fugtprofilet for en given plade med en given tykkelse og diffusionskoefficient som funktion af tiden.

Tallene foreligger også i tabelform. I bilag 13 er

$$\frac{u(r,t) - u_\infty}{u_0 - u_\infty} \tag{3.1}$$

tabelleret for $0 \leq Fo \leq 0.5$ med spring i Fo på 0.00125.



Figur 6. Fugtfordeling til givne tidspunkter i en uendeligt lang plade med startvandindhold u_o og overfladevandindhold u_∞. Tallene på kurverne er $Fo = Dt/L^2$.

I bilag 14 er 3.1 tabellag for $0 \leq Fo \leq 1.5$ med spring i Fo på 0.01.

3.3 Uddata fra MEANMOIS

Et eksempel på uddata fra MEANMOIS er anbragt i bilag 12. På grundlag af disse uddata er der fremstillet kurver over middelvandindholdet i plade, cylinder- og kugletilfældet som vist i figur 7. Man går ind i diagrammet med den dimensionsløse størrelse

$$Fo = Dt/\delta^2$$

hvor δ er den karakteristiske dimension i henholdsvis plade-, cylinder- og kugletilfældet. Man kan da på de respektive kurver aflæse størrelsen U_m, der er givet som

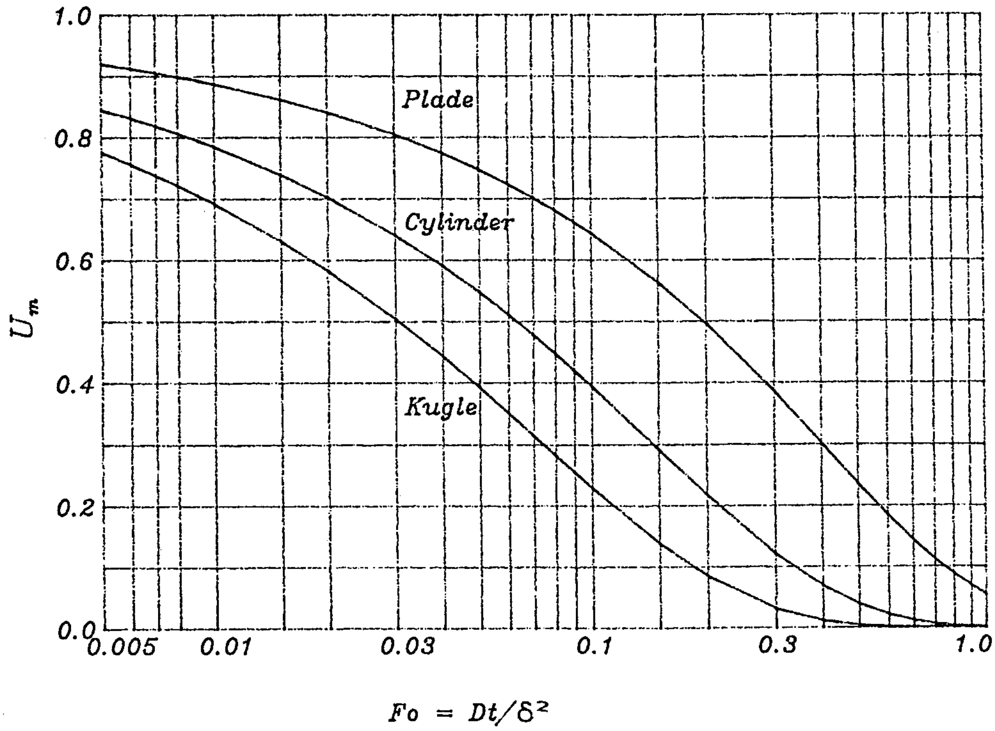
$$U_m = \frac{u_m(t) - u_\infty}{u_0 - u_\infty}$$

hvor

$u_m(t)$ = konstruktionens middelvandindhold

u_∞ = slutvandindhold

u_o = begyndelsesvandindhold



Figur 7. Kurver over middelvandindhold.

4. LITTERATURFORTEGNELSE

/1/ Crank, J.: "The Mathematics of Diffusion". Oxford University Press, Oxford, 1975.

/2/ Hansen, E.: "Sædvanlige differentialligninger fra fysikken". Polyteknisk Forlag, Lyngby, 1976.

/3/ Hansen, P.N.: "Termiske beregningsmetoder". Laboratoriet for Varmeisolering, Danmarks tekniske Højskole, Notat til kurset Varmeisolering II, Lyngby, 1978.

/4/ Ames, W.F.: "Numerical Methods for Partial Differential Equations". John Wiley, London, 1977.

/5/ Nielsen, Hans Bruun: "Numerisk løsning af partielle differentialligninger". Numerisk Institut, Danmarks tekniske Højskole, Hæfte 39, Lyngby, 1977.

/6/ Nielsen, Hans Bruun: "Løsning af lineære ligningssystemer". Numerisk Institut, Danmarks tekniske Højskole, Hæfte 23, Lyngby, 1972.

/7/ Hansen, M.H., og Hansen, K.K.: "Sammenligning af simpel model for fugttransport og fugttransport beskrevet ved lineær diffusionsteori". Laboratoriet for Bygningsmaterialer, Danmarks tekniske Højskole, Teknisk Rapport 178/88, Lyngby, 1988.

BILAG 1. DIFFERENSLIGNING FOR u_o

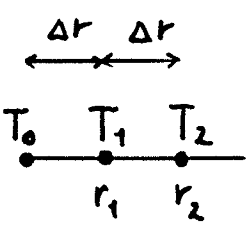
Dette bilag beskriver, hvordan der kan opstilles en differensligning med endelige differensers metode til bestemmelse af vandindholdet i centrum af en cylinder, hvori der foregår endimensional fugttransport beskrevet ved diffusionsligningen

$$\frac{\partial u}{\partial t} = D\left(\frac{1}{r}\frac{\partial u}{\partial x} + \frac{\partial^2 u}{\partial x^2}\right) \qquad (2.5)$$

Der er valgt en eksplicit endelige differensers metode. Bestemmelsen sker ud fra et ræsonnement, som bygger på analogien diffusion af temperatur i en cylinder.

Opstilles differensligningen 2.10 for temperaturen i punktet T_1, fås (jvf. figur B1)

$$\rho c_p \frac{T_1^{t_1+\Delta t} - T_1^{t_1}}{\Delta t} = \lambda\left(\frac{1}{r_1}\frac{T_2^{t_1} - T_0^{t_1}}{2\Delta r} + \frac{T_2^{t_1} + T_0^{t_1} - 2T_1^{t_1}}{(\Delta r)^2}\right) \qquad (B1)$$



Figur B1. Punktbetegnelse.

Energifluxen for punkt 1 til punkt 2 er

$$\dot{q}_{1\to 2} = \frac{2\pi\lambda (T_1 - T_2)}{\ln(r_2/r_1)} \qquad (B2)$$

Arealflade 1 (vedrørende fladebetegnelse, se figur B2).

$$A_1 = \pi\left(\left(\frac{r_1 + r_2}{2}\right)^2 - \left(\frac{r_1}{2}\right)^2\right)$$

$$= \frac{\pi r_2}{2}\left(\frac{r_2}{2} + r_1\right) \qquad (B3)$$

Arealflade 0

$$A_0 = \pi \frac{r_1^2}{4} \qquad (B4)$$

Energitilvækst flade 1 for t_1 --> t_1 + t

$$\Delta \dot{q}_1 = A_1 \frac{\rho c_p}{\Delta t}\left(T_1^{t_1 + \Delta t} - T_1^{t_1}\right) \qquad (B5)$$

Energitilvækst flade 0 for t_1 --> t_1 + t

$$\Delta \dot{q}_0 = A_0 \frac{\rho c_p}{\Delta T}\left(T_0^{t_1 + \Delta t} - T_0^{t_1}\right) \qquad (B6)$$

En energibalance for flade 1 og 0 giver

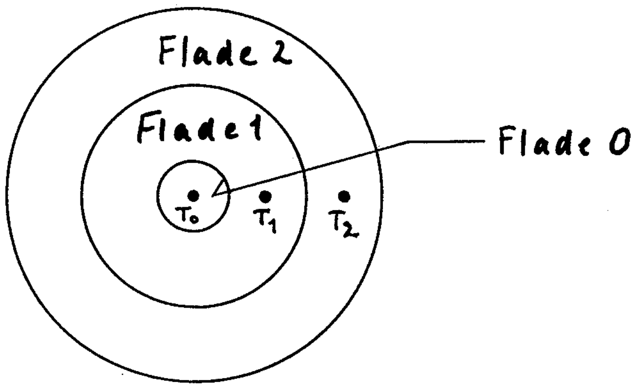
$$\Delta \dot{q}_0 + \Delta \dot{q}_1 + \dot{q}_{1\to 2} = 0 \qquad (B7)$$

Indsættes B6, B5 og B2 i B7, fås

$$A_0 \frac{\varrho c_p}{\Delta t}\left(T_0^{t_1+\Delta t} - T_0^{t_1}\right) + A_1 \frac{\varrho c_p}{\Delta t}\left(T_1^{t_1+\Delta t} - T_1^{t_1}\right) + \frac{2\pi\lambda\left(T_1^{t_1} - T_2^{t_1}\right)}{\ln(r_2/r_1)} = 0 \qquad \text{(B8)}$$

Indsættes B1, B3 og B4 i B8, fås

$$\pi \frac{r_1^2}{4} \frac{\varrho c_p}{\Delta t}\left(T_0^{t_1+\Delta t} - T_0^{t_1}\right) + \frac{\pi r_2}{2}\left(\frac{r_2}{2} + r_1\right) \cdot \lambda\left(\frac{1}{r_1}\frac{T_2^{t_1} - T_0^{t_1}}{2\Delta r} + \frac{T_2^{t_1} + T_0^{t_1} - 2T_1^{t_1}}{(\Delta r)^2}\right) + \frac{2\pi\lambda\left(T_1^{t_1} - T_2^{t_1}\right)}{\ln(r_2/r_1)} = 0 \qquad \text{(B9)}$$



Figur B2. Fladebetegnelse.

For r_2/r_1 = 2, altså konstant r konstant, bliver B9

$$\frac{r_1^2}{4}\frac{\rho c_p}{\Delta t}\left(T_0^{t_1+\Delta t}-T_0^{t_1}\right)+2r_1^2\lambda\left(\frac{1}{r_1}\frac{T_2^{t_1}-T_0^{t_1}}{2\Delta r}+\frac{T_2^{t_1}+T_0^{t_1}-2T_1^{t_1}}{(\Delta r)^2}\right)+\frac{2\lambda\left(T_1^{t_1}-T_2^{t_1}\right)}{\ln 2}=0 \qquad (B10)$$

Idet r = r_1, bliver B10

$$\frac{r_1^2}{4}\frac{\rho c_p}{\Delta t}\left(T_0^{t_1+\Delta t}-T_0^{t_1}\right)+\lambda\left(T_2^{t_1}-T_0^{t_1}+2\left(T_2^{t_1}+T_0^{t_1}-2T_1^{t_1}\right)\right)+\frac{2\lambda\left(T_1^{t_1}-T_2^{t_1}\right)}{\ln 2}=0 \Leftrightarrow$$

$$\frac{r_1^2}{4}\frac{\rho c_p}{\Delta t}\left(T_0^{t_1+\Delta t}-T_0^{t_1}\right)+\lambda\left(T_0^{t_1}+\left(\frac{2}{\ln 2}-4\right)T_1^{t_1}+\left(3-\frac{2}{\ln 2}\right)T_2^{t_1}\right)=0 \Leftrightarrow$$

$$T_0^{t_1+\Delta t}=T_0^{t_1}-\frac{4\kappa\Delta t}{r_1^2}\left(T_0^{t_1}+\left(\frac{2}{\ln 2}-4\right)T_1^{t_1}+\left(3-\frac{2}{\ln 2}\right)T_2^{t_1}\right) \qquad (B11)$$

Da r_1 = r, og når der anvendes vandindholdet u som potentiale, fås

$$u_0^{t_1+\Delta t}=u_0^{t_1}-\frac{4D\Delta t}{(\Delta r)^2}\left(u_0^{t_1}+\left(\frac{2}{\ln 2}-4\right)u_1^{t_1}+\left(3-\frac{2}{\ln 2}\right)u_2^{t_1}\right) \qquad (B12)$$

Stabilitetskravet for B12 er

$$1-\frac{4D\Delta t}{(\Delta r)^2}>0$$

```
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     NUMERISK L/SNING AF DIFFUSIONSLIGNING
C     CYLINDERKOORDINATER
C     1-DIMENSIONALT
C     EKSPLICIT METODE
C     FAST LAGTYKKELSE
C     FAST TIDSSKRIDT
C
C     MORTEN HJORSLEV HANSEN
C     LABORATORIET FOR BYGNINGSMATERIALER 1987
C
C     VERSION 2       6/10-1987
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      REAL*4 U(0:50),UNY(0:50)
      OPEN(6,FILE='A:CYLDIF.UD',STATUS='NEW')
      OPEN(7,FILE='A:CYLDIF.UD1',STATUS='NEW')
      OPEN(8,FILE='A:CYLDIF.UD2',STATUS='NEW')
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     STYRING AF NETINDDELING
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      N=10
      N1=N-1
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     DIFFUSIONSKOEFFICIENT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      ALFA=1.0E-7
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     NETINDDELING
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
       DELTAR=1.0/FLOAT(N)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     TIDSSKRIDT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DELTI=20000.0
      TID=0.0
      TIDMAX=550.*DELTI
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     BEGYNDELSESBETINGELSER
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      USTART=0.3
      USLUT=0.1
      DO 10 I=0,N
```

```
      U(I)=USTART
   10 UNY(I)=USTART
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     RANDBETINGELSER
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      U(N)=USTART
      UNY(N)=U(N)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     UDSKRIVNING AF BEGYNDELESFUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      WRITE(6,25) TID,(U(I),I=0,4)
   25 FORMAT(' ',F9.0,5F11.6)
      WRITE(7,30) TID,(U(I),I=5,10)
   30 FORMAT (' ',F9.0,6F11.6)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     BEREGNINGSL/KKE
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OPSKRIVNING AF TID
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
    5 TID=TID+DELTI
      U(N)=URB(TID)
      DO 20 I=1,N1
         UNY(I)=(U(I+1)+U(I-1)-2*U(I))/(DELTAR**2)
         UNY(I)=UNY(I)+(U(I+1)-U(I-1))/(2*FLOAT(I)*DELTAR**2)
   20    UNY(I)=U(I)+UNY(I)*ALFA*DELTI
      UNY(0)=U(0)-(4*ALFA*DELTI/DELTAR**2)*(U(0)+(2.0/ALOG(2.0)
     $       -4.0)*U(1)+(3.0-2.0/ALOG(2.0))*U(2))
      FO=ALFA*TID
      ARG=(U(0)-U(5))/(U(0)-U(N))
      IF (ARG.LE.0.0) THEN
         XN=0.0
      ELSE
         XN=ALOG(ARG)/ALOG(0.5)
      ENDIF
      IF ((USTART-U(0)).LE.0.0) THEN
         ALFAC=0.0
      ELSE
         ALFAC=-TID/ALOG(1.0-(USTART-U(0))/(USTART-USLUT))
      ENDIF
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OMBYTNING AF FUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DO 40 I=0,N1
   40    U(I)=UNY(I)
C
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     UDSKRIVNING AF FUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      WRITE(6,50) TID,(U(I),I=0,4)
   50 FORMAT(' ',F9.0,5F11.6)
      WRITE(7,60) TID,(U(I),I=5,10)
   60 FORMAT (' ',F9.0,6F11.6)
      WRITE(8,70) TID,XN,ALFAC,FO
   70 FORMAT(' ',F9.0,F11.5,E16.6,F11.6)
      IF (TID.LT.TIDMAX) GOTO 5
      STOP
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINER
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     FUNCTION URB
C     GIVER RANDBETINGELSEN PÅ CYLINGERENS OVERFLADE
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      FUNCTION URB(TID)
      ALFAO=40.0*24.0*3600.0
      USTART=0.30
      USLUT=0.10
      URB=USLUT+(USTART-USLUT)*EXP(-TID/ALFAO)
      RETURN
      END
```

BILAG 3

KONTROL AF CYLDIF

Tids-punkt [s]	Radius [-]	"Analytisk"** løsning u [-]	Numerisk løsning u [-]	Numerisk løsning (DP)* u [-]
r = 1/10	t = 900 s			
54000	0	0.295344954	0.29538113	0.29538259
89100	0	0.290003032	0.29004008	0.29004228
89100	0.5	0.286741080	0.28670764	0.28670928
89100	0.9	0.281318333	0.28131056	0.28131102
r = 1/10	t = 900			
10800	0	0.299998841	0.29999942	0.29999975
21600	0	0.29977652	0.29979372	0.29979360
21600	0.5	0.296859640	0.29675990	0.29676044
21600	0.9	0.284163338	0.28410345	0.28410371
r = 1/10	t = 450			
10800	0	0.299998841	0.29999715	0.29999763
21600	0	0.299776562	0.29975724	0.29975834
21600	0.5	0.296859640	0.29676867	0.29676978
21600	0.9	0.284163338	0.28414148	0.28414199
r = 1/20	t = 225			
10800	0	0.299998841	0.29999757	0.29999890
21600	0	0.299776562	0.29977918	0.29978162
21600	0.5	0.296859640	0.29683250	0.29683478
21600	0.9	0.284163338	0.28414708	0.28414807

* DP = double precision **Jvf. ligning 2.8

```
      PROGRAM CARDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     NUMERISK LØSNING AF DIFFUSIONSLIGNING
C     KARTESISKE KOORDINATER
C     1-DIMENSIONALT
C     IMPLICET METODE
C     FAST LAGTYKKELSE
C     FAST TIDSSKRIDT
C
C     MORTEN HJORSLEV HANSEN
C     LABORATORIET FOR BYGNINGSMATERIALER 1987
C
C     VERSION 1.0 23/9-87
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      REAL*8 U(50),UNY(50),A(50),B(50),C(50),D(50),E(50),G(50)
      REAL*8 ALFA,DELTAX,DELTI,TID,TIDMAX,R,VRB,HRB
      OPEN(6,FILE='A:CARDIF.UD',STATUS='OLD')
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     STYRING AF NETINDDELING
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      N=10
      N1=N-1
      N2=N-2
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     DIFFUSIONSKOEFFICIENT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      ALFA=1.0D0
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     NETINDDELING
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DELTAX=1.0D0/DFLOAT(N)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     TIDSSKRIDT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DELTI=DELTAX**2
      TID=0.0D0
      TIDMAX=10.0D0*DELTI
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OPSTILLING AF KOEFFICIENTMATRIX
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      R=ALFA*DELTI/DELTAX**2
      B(1)=2.0D0+2.0D0*R
      C(1)=-R
```

```
      DO 1000 I=2,N2
         A(I)=-R
         B(I)=B(1)
 1000    C(I)=-R
      A(N1)=-R
      B(N1)=B(1)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     GAUSSELIMINATION AF KOEFFICIENTMATRIX
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      CALL FAKT(A,B,C,E,G,N1)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     BEGYNDELSESBETINGELSER
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C       DO 10 I=1,N1
C   10     U(I)=1.0D0
      U(1)=0.2D0
      U(2)=0.4D0
      U(3)=0.6D0
      U(4)=0.8D0
      U(5)=1.0D0
      U(6)=0.8D0
      U(7)=0.6D0
      U(8)=0.4D0
      U(9)=0.2D0
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     UDSKRIVNING AF OVERSKRIFT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      WRITE(6,28)
   28 FORMAT('X = 0.0',3X,'0.1',4X,'0.2',4X,'0.3',4X,'0.4',4X,'0.5',4X,
     &'0.6',4X,'0.7',4X,'0.8',4X,'0.9',4X,'1.0'/)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     UDSKRIVNING AF FUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
    5 WRITE(6,25) TID
   25 FORMAT(' ','TIDSPUNKT = ',F9.3,'S'/)
C      WRITE(6,28)
C   28 FORMAT(' ',19X,'X/L =',5X,'0.0',6X,'0.1',6X,'0.2',6X,'0.3',6X,
C     &'0.4',6X,'0.5',6X,'0.6',6X,'0.7',6X,'0.8',6X,'0.9',6X,'1.0'//
C     &9X,'T',12X,'FO'/)
C    5 FO=4.0D0*TID
      WRITE(6,30) VRB(TID),(U(I),I=1,N1),HRB(TID)
   30 FORMAT (11F7.4//)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     BEREGNINGSLØKKE
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      D(1)=R*VRB(TID)+(2.0D0-2.0D0*R)*U(1)+R*U(2)
```

```
      DO 35 I=2,N2
   35    D(I)=R*U(I-1)+(2.0D0-2.0D0*R)*U(I)+R*U(I+1)
      D(N1)=R*U(N2)+(2.0D0-2.0D0*R)*U(N1)+R*HRB(TID)
      CALL LOES(A,D,E,G,UNY,N1)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OMBYTNING AF FUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DO 40 I=1,N1
   40    U(I)=UNY(I)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OPSKRIVNING AF TID
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      TID=TID+DELTI
      IF (TID.LE.TIDMAX) GOTO 5
      STOP
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINER
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE FAKT
C     GAUSSELIMINERER KOEFFICIENTMATRIX I LIGNINGSSYTEM, HVOR DENNE ER EN
C     TRIDIAGONALMATRIX
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE FAKT(A,B,C,E,G,N)
      REAL*8 A(N),B(N),C(N),E(N),G(N)
      N1=N-1
      G(1)=B(1)
      E(1)=C(1)/G(1)
      DO 10 I=2,N1
         G(I)=B(I)-A(I)*E(I-1)
   10    E(I)=C(I)/G(I)
      G(N)=B(N)-A(N)*E(N1)
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     SUBROUTINE LOES
C     GAUSSELIMINERER HØJRESIDEN I LIGNINGSSYTEM, HVOR KOEFFICIENTMATRI-
C     CEN ER EN TRIDIAGONALMATRIX, OG LØSERLIGNINGSSYSTEMET
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE LOES(A,D,E,G,X,N)
      REAL*8 A(N),D(N),E(N),F(50),G(N),X(N)
      N1=N-1
      F(1)=D(1)/G(1)
      DO 10 I=2,N
   10    F(I)=(D(I)-A(I)*F(I-1))/G(I)
```

```
C
C     BACKSUBSTITUTION
C
      X(N)=F(N)
      DO 20 I=N1,1,-1
   20    X(I)=F(I)-E(I)*X(I+1)
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C    FUNCTION VRB
C    GIVER RANDBETINGELSEN I VENSTRE SIDE AF PLADEN SOM EN FUNKTION AF
C    TIDEN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DOUBLE PRECISION FUNCTION VRB(TID)
      REAL*8 TID
      VRB=0.0D0
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C    FUNCTION HRB
C    GIVER RANDBETINGELSEN I HØJRE SIDE AF PLADEN SOM EN FUNKTION AF
C    TIDEN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DOUBLE PRECISION FUNCTION HRB(TID)
      REAL*8 TID
      HRB=0.0D0
      RETURN
      END
```

Bilag 5 **Kontrol af CARDIF**

X = 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
TIDSPUNKT =		.000S								
.0000	.2000	.4000	.6000	.8000	1.0000	.8000	.6000	.4000	.2000	.0000
TIDSPUNKT =		.010S								
.0000	.1989	.3956	.5834	.7381	.7691	.7381	.5834	.3956	.1989	.0000
TIDSPUNKT =		.020S								
.0000	.1936	.3789	.5397	.6461	.6921	.6461	.5397	.3789	.1936	.0000
TIDSPUNKT =		.030S								
.0000	.1826	.3515	.4902	.5843	.6152	.5843	.4902	.3515	.1826	.0000
TIDSPUNKT =		.040S								
.0000	.1683	.3218	.4461	.5267	.5555	.5267	.4461	.3218	.1683	.0000
TIDSPUNKT =		.050S								
.0000	.1538	.2932	.4047	.4770	.5019	.4770	.4047	.2932	.1538	.0000
TIDSPUNKT =		.060S								
.0000	.1399	.2664	.3672	.4321	.4546	.4321	.3672	.2664	.1399	.0000
TIDSPUNKT =		.070S								
.0000	.1270	.2418	.3330	.3916	.4119	.3916	.3330	.2418	.1270	.0000
TIDSPUNKT =		.080S								
.0000	.1153	.2193	.3019	.3550	.3733	.3550	.3019	.2193	.1153	.0000
TIDSPUNKT =		.090S								
.0000	.1045	.1989	.2738	.3219	.3385	.3219	.2738	.1989	.1045	.0000

BILAG 6

TRANSFORMATION AF KUGLETILFÆLDET TIL PLADETILFÆLDET

Givet den lineære partielle differentialligning for endimensional diffusion i en kugle

$$\frac{\partial u}{\partial t} = D\left(\frac{\partial^2 u}{\partial x^2} + \frac{2}{x}\frac{\partial u}{\partial x}\right) \qquad (*)$$

Ved anvendelse af transformationen w = ux fås for x = 0

$$u = \frac{w}{x}$$

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial t}\left(\frac{w}{x}\right) = \frac{1}{x}\frac{\partial w}{\partial t}$$

$$\frac{\partial u}{\partial x} = \frac{\partial}{\partial x}\frac{w}{x} = \frac{1}{x}\frac{\partial w}{\partial x} - \frac{w}{x^2}$$

$$\frac{\partial^2 u}{\partial x^2} = \frac{\partial}{\partial x}\frac{\partial u}{\partial x} = \frac{\partial}{\partial x}\left(\frac{1}{x}\frac{\partial w}{\partial x} - \frac{w}{x^2}\right)$$

$$= -\frac{1}{x^2}\frac{\partial w}{\partial x} + \frac{1}{x}\frac{\partial^2 w}{\partial x^2} - \frac{\partial w}{\partial x}\frac{1}{x^2} + \frac{2}{x^3}w$$

Ved at indsætte i (*) fås

$$\frac{\partial w}{\partial t} = D\frac{\partial^2 w}{\partial x^2}$$

hvilket er den lineære partielle differentialligning for endimensional diffusion i en plade.

MIDELVANDINDHOLD I PLADETILFÆLDET

Fugtfordelingen i uendelig plade med tykkelsen 2δ

$$\frac{u - u_\infty}{u_0 - u_\infty} = -\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n-1)}e^{-[(2n-1)\pi/2\delta]^2\alpha t} \cdot \cos\left(\frac{2n-1}{2\delta}\pi x\right)(-1)^n$$

$$u(x,t) = u_\infty + (u_0 - u_\infty)\,f(x,t)$$

$$f(x,t) = -\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n-1)}e^{-[(2n-1)\pi/2\delta]^2\alpha t} \cdot \cos\left(\frac{2n-1}{2\delta}\pi x\right)(-1)^n$$

Middelfugtindholdet er givet ved

$$\bar{u} = \frac{1}{\delta - 0}\int_0^\delta u(x,t)\,dx$$

$$= \frac{1}{\delta}\int_0^\delta u(x,t)\,dx$$

$$= \frac{1}{\delta}\int_0^\delta \left[u_\infty + (u_0 - u_\infty)f(x,t)\right]dx$$

$$= \frac{1}{\delta}\left[u_\infty x\right]_0^\delta + \frac{u_0 - u_\infty}{\delta}\int_0^\delta f(x,t)\,dx$$

$$= u_\infty + \frac{u_0 - u_\infty}{\delta}\int_0^\delta f(x,t)\,dx$$

$$\int_0^\delta -\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n-1}\cos\left(\frac{2n-1}{2\delta}\pi x\right)e^{-[(2n-1)\pi/2\delta]^2\alpha t}\,dx =$$

$$-\frac{4}{\pi}\sum_{n=1}^{\infty}\int_0^\delta\frac{(-1)^n}{2n-1}\cos\left(\frac{2n-1}{2\delta}\pi x\right)e^{-[(2n-1)\pi/2\delta]^2\alpha t}\,dx =$$

$$-\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n-1}e^{-[(2n-1)\pi/2\delta]^2\alpha t}\left[\frac{2\delta}{(2n-1)\pi}\sin\left(\frac{2n-1}{2\delta}\pi x\right)\right]_0^\delta =$$

$$-\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n-1}e^{-[(2n-1)\pi/2\delta]^2\alpha t}\frac{2\delta}{(2n-1)\pi}\sin(n-\tfrac{1}{2})\pi =$$

$$-\frac{8\delta}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n-1)^2}e^{-[(2n-1)\pi/2\delta]^2\alpha t}\sin(n-\tfrac{1}{2})\pi =$$

$$\frac{8\delta}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}e^{-[(2n-1)\pi/2\delta]^2\alpha t}$$

n	$(n-\frac{1}{2})\pi$	$\sin(n-\frac{1}{2})\pi$	$(-1)^n$	$(-1)^n\sin(n-\frac{1}{2})\pi$
1	$\frac{\pi}{2}$	1	−1	−1
2	$\frac{3\pi}{2}$	−1	1	−1
3	$\frac{5\pi}{2}$	1	−1	−1
4	$\frac{7\pi}{2}$	−1	1	−1

$$\bar{u} = u_\infty + \frac{u_0 - u_\infty}{\delta}\,\frac{8\delta}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}e^{-[(2n-1)\pi/2\delta]^2\alpha t}$$

$$= u_\infty + 8\,\frac{u_0 - u_\infty}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}e^{-[(2n-1)\pi/2\delta]^2\alpha t}$$

BILAG 8

MIDDELVANDINDHOLD I CYLINDERTILFÆLDET

Fugtfordelingen i en uendeligt lang cylinder med radius R er givet som

$$\frac{u - u_\infty}{u_o - u_\infty} = 2 \sum_{n=1}^{\infty} \frac{1}{\beta_n} e^{-(\beta_n/R)^2 \alpha t} \frac{J_o[\beta_n (r/R)]}{J_1(\beta_n)}$$

Middelfugtindholdet i cylinderen er givet som

$$\bar{u} = \frac{\int_0^{2\pi} \int_0^R u(r,t)\, r\, dr\, d\Theta}{\int_0^{2\pi} \int_0^R r\, dr\, d\Theta}$$

$$= \frac{2\pi \int_0^R u(r,t)\, r\, dr}{\pi R^2}$$

$$= \frac{2}{R^2} \int_0^R u(r,t)\, r\, dr$$

$$\int_0^R u(R,t)\,r\,dr = \int_0^R \left[u_\infty + (u_0 - u_\infty)\, 2 \sum_{n=1}^{\infty} \frac{1}{\beta_n} e^{-(\beta_n/R)^2 \alpha t} \, \frac{J_0[\beta_n(r/R)]}{J_1(\beta_n)}\right] r\,dr =$$

$$\left[\tfrac{1}{2} u_\infty r^2\right]_0^R + 2(u_0 - u_\infty) \int_0^R \sum_{n=1}^{\infty} \frac{1}{\beta_n} e^{-(\beta_n/R)^2 \alpha t} \, \frac{J_0[\beta_n(r/R)]}{J_1(\beta_n)}\, r\,dr =$$

$$\left[\tfrac{1}{2} u_\infty r^2\right]_0^R + 2(u_0 - u_\infty) \sum_{n=1}^{\infty} \int_0^R \frac{1}{\beta_n} e^{-(\beta_n/R)^2 \alpha t} \, \frac{J_0[\beta_n(r/R)]}{J_1(\beta_n)}\, r\,dr =$$

$$\tfrac{1}{2} u_\infty R^2 + 2(u_0 - u_\infty) \sum_{n=1}^{\infty} \frac{1}{\beta_n} \frac{e^{-(\beta_n/R)^2 \alpha t}}{J_1(\beta_n)} \int_0^R J_0[\beta_n(r/R)]\, r\,dr =$$

$$\tfrac{1}{2} u_\infty R^2 + 2(u_0 - u_\infty) \sum_{n=1}^{\infty} \frac{1}{\beta_n} \frac{e^{-(\beta_n/R)^2 \alpha t}}{J_1(\beta_n)} \left(\frac{R}{\beta_n}\right)^2 \int_0^R \frac{r\beta_n}{R} J_0\big(\beta_n(r/R)\big)\, d\!\left(\frac{r\beta_n}{R}\right) =$$

$$\tfrac{1}{2} u_\infty R^2 + 2(u_0 - u_\infty) \sum_{n=1}^{\infty} \frac{1}{\beta_n} \frac{e^{-(\beta_n/R)^2 \alpha t}}{J_1(\beta_n)} \left(\frac{R}{\beta_n}\right)^2 \left[\frac{r\beta_n}{R} J_1[\beta_n(r/R)]\right]_0^R =$$

$$\tfrac{1}{2} u_\infty R^2 + 2(u_0 - u_\infty) \sum_{n=1}^{\infty} \frac{1}{\beta_n} \frac{e^{-(\beta_n/R)^2 \alpha t}}{J_1(\beta_n)} R^2 J_1(\beta) =$$

$$\tfrac{1}{2} u_\infty R^2 + 2(u_0 - u_\infty) R^2 \sum_{n=1}^{\infty} \frac{e^{-(\beta_n/R)^2 \alpha t}}{\beta_n^2}$$

d.v.s.

$$\bar{u} = u_\infty + 4(u_0 - u_\infty) \sum_{n=1}^{\infty} \frac{e^{-(\beta_n/R)^2 \alpha t}}{\beta_n^2}$$

Integration af J_0 jvf. /2/

Erik Hansen p. 311

BILAG 9

MIDDELVANDINDHOLD I EN KUGLE

Fugtfordelingen i en kugle er givet ved

$$\frac{u - u_\infty}{u_0 - u_\infty} = \frac{2}{\pi}\frac{R}{r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) \Leftrightarrow$$

$$u(r,t) = u_\infty + (u_0 - u_\infty) f(r,t)$$

hvor

$$f(r,t) = \frac{2}{\pi}\frac{R}{r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)$$

idet

$$x^2 + y^2 + z^2 = r^2 \Leftrightarrow$$

$$r = \sqrt{x^2 + y^2 + z^2}$$

Middelfugtindholdet i kuglen er givet ved udtrykket

$$\bar{u}(t) = \frac{\iiint_A u(r,t)\,dx\,dy\,dz}{vol(A)} =$$

$$\frac{\int_0^R \int_0^{2\pi} \left[\int_0^{\pi} \left[u_\infty + (u_0 - u_\infty)\frac{2}{\pi}\frac{R}{r}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)\right] r^2 \sin\theta \, dr\, d\theta\, d\varphi \right.}{\frac{4}{3}\pi R^3}$$

$$= \frac{\frac{4}{3}\pi R^3 u_\infty + 8(u_0 - u_\infty)\frac{R^3}{\pi}\sum_{n=1}^{\infty}\frac{1}{n^2} e^{-(n\pi/R)^2 \alpha t}}{\frac{4}{3}\pi R^3}$$

$$= u_\infty + \frac{6}{\pi^2}(u_0 - u_\infty)\sum_{n=1}^{\infty}\frac{1}{n^2} e^{-(n\pi/R)^2 \alpha t}$$

$$\int_0^R \int_0^{2\pi} \left[\int_0^{\pi} \left[u_\infty + (u_0 - u_\infty) \frac{2}{\pi} \frac{R}{r} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \; e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)\right] r^2 \sin\theta \, d\theta \right] dr \, d\phi$$

$$= \int_0^R \int_0^{2\pi} \left[\left[u_\infty + (u_0 - u_\infty) \frac{2}{\pi} \frac{R}{r} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)\right] r^2 (-\cos\theta\right]_0^{\pi} dr \, d\phi$$

$$= \int_0^R \left[\int_0^{2\pi} \left[2r^2 u_\infty + (u_0 - u_\infty) \frac{4}{\pi} R r \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \; e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)\right] d\phi \right] dr$$

$$= 2\pi \int_0^R \left[2r^2 u_\infty + (u_0 - u_\infty) \frac{4}{\pi} R r \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)\right] dr$$

$$= 2\pi \left[2 \frac{r^3}{3} u_\infty \right]_0^R + 2\pi (u_0 - u_\infty) \frac{4}{\pi} R \int_0^R r \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) dr$$

$$= \frac{4}{3} \pi^2 R^3 u_\infty + 8 (u_0 - u_\infty) R \int_0^R r \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) dr$$

$$= \frac{4}{3} \pi R^3 u_\infty + 8 (u_0 - u_\infty) R \left[-\frac{rR}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right) + \right.$$
$$\left. \frac{R^2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^3} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) \right]_0^R$$

$$= \frac{4}{3} \pi R^3 u_\infty + 8 (u_0 - u_\infty) R \left[-\frac{R^2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos(n\pi) + \right.$$
$$\left. \frac{R^2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^3} e^{-(n\pi/R)^2 \alpha t} \sin(n\pi) \right]$$

$$= \frac{4}{3} \pi R^3 u_\infty + 8 (u_0 - u_\infty) R \left[-\frac{R^2}{\pi} \sum_{n=1}^{\infty} \frac{-1}{n^2} e^{-(n\pi/R)^2 \alpha t} \right]$$

$$= \frac{4}{3} \pi R^3 u_\infty + 8 (u_0 - u_\infty) \frac{R^3}{\pi} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/R)^2 \alpha t}$$

Mellemresultater:

$$\int r \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) dr =$$

$$r \int \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) dr - \int -\frac{R}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right) dr$$

$$= -\frac{rR}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right) + \frac{R}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi R)^2 \alpha t} \int \cos\left(\frac{n\pi}{R} r\right) dr$$

$$= -\frac{rR}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right) + \frac{R}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \frac{R}{n\pi} \sin\left(\frac{n\pi}{R} r\right)$$

$$= -\frac{rR}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right) + \frac{R^2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^3} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right)$$

$$\int \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \sin\left(\frac{n\pi}{R} r\right) dr =$$

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \int \sin\left(\frac{n\pi}{R} r\right) dr =$$

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-(n\pi/R)^2 \alpha t} \left(-\frac{R}{n\pi} \cos\left(\frac{n\pi}{R} r\right)\right) =$$

$$-\frac{R}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-(n\pi/R)^2 \alpha t} \cos\left(\frac{n\pi}{R} r\right)$$

n	$n\pi$	$n+1$	$(-1)^{n+1}$	$\cos(n\pi)$	$\sin(n\pi)$	$(-1)^{n+1}\cos(n\pi)$
1	π	2	1	−1	0	(−1)
2	2π	3	−1	1	0	(−1)
3	3π	4	1	−1	0	(−1)
4	4π	5	−1	1	0	(−1)
5	5π	6	1	−1	0	(−1)

```
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      PROGRAM TIL BEREGNING AF ANALYSTISKE UDTRYK TIL BESKRIVELSE AF
C      MIDDELFUGTINDHOLDET I EN PLADE, EN CYLINDER OG EN KUGLE.
C
C      MORTEN HJORSLEV HANSEN
C      LABORATORIET FOR BYGNINGSMATERIALER SEPTEMBER 1987
C      VERSION 1.0 19/10-87
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      INTEGER I,N,IER,NFO,NPLADE,NCYL,NKUGLE
      REAL*8 FO(35),BETA(20),RODARG,PI,ARG
      REAL*8 UPLADE,UKUGLE,UCYL
      OPEN(6,FILE='A:MEANMOIS.UD',STATUS='OLD')
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      INITIALISERING
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      PI=3.141592653589793
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      ANTAL FOURIERTAL
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      NFO=35
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      R/DDER AF BESSELFUNKTIONEN AF 0'TE ORDEN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      BETA(1)=2.4048D0
      BETA(2)=5.5201D0
      BETA(3)=8.6537D0
      BETA(4)=11.7915D0
      BETA(5)=14.9309D0
      BETA(6)=18.0711D0
      BETA(7)=21.2116D0
      BETA(8)=24.3525D0
      BETA(9)=27.4935D0
      BETA(10)=30.6346D0
      BETA(11)=33.7758D0
      BETA(12)=36.9171D0
      BETA(13)=40.0584D0
      BETA(14)=43.1998D0
      BETA(15)=46.3412D0
      BETA(16)=49.4826D0
      BETA(17)=52.6241D0
      BETA(18)=55.7655D0
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      FOURIERTAL
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      FO(1)=0.0015D0
      FO(2)=0.002D0
```

```
      FO(3)=0.003D0
      FO(4)=0.004D0
      FO(5)=0.005D0
      FO(6)=0.006D0
      FO(7)=0.007D0
      FO(8)=0.008D0
      FO(9)=0.009D0
      FO(10)=0.01D0
      FO(11)=0.015D0
      FO(12)=0.02D0
      FO(13)=0.03D0
      FO(14)=0.04D0
      FO(15)=0.05D0
      FO(16)=0.06D0
      FO(17)=0.07D0
      FO(18)=0.08D0
      FO(19)=0.09D0
      FO(20)=0.10D0
      FO(21)=0.15D0
      FO(22)=0.2D0
      FO(23)=0.3D0
      FO(24)=0.4D0
      FO(25)=0.5D0
      FO(26)=0.6D0
      FO(27)=0.7D0
      FO(28)=0.8D0
      FO(29)=0.9D0
      FO(30)=1.0D0
      FO(31)=1.1D0
      FO(32)=1.2D0
      FO(33)=1.3D0
      FO(34)=1.4D0
      FO(35)=1.5D0
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     OVERSKRIFT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      WRITE(6,9)
    9 FORMAT(4X,'FO',7X,'UM',7X,'UM',7X,'UM',7X,'N',7X,'N',7X,'N'/
     &12X,'PLADE',2X,'CYLINDER',3X,'KUGLE',3X,'PLADE',1X,'CYLINDER',2X
     &,'KUGLE'/)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     BEREGNING AF MIDDELFUGTINDHOLD
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DO 10 I=1,NFO
         RODARG=DSQRT(-DLOG(1.0D-60)/FO(I))
         NPLADE=INT(0.5D0*(1.0D0+2.0D0/PI*RODARG))
         NCYL=MIN0(18,INT(RODARG/3.0D0))
         NKUGLE=INT(RODARG/PI)
         UPLADE=0.0D0
         DO 20 J=1,NPLADE
            ARG=2.0D0*DFLOAT(J)-1.0D0
   20      UPLADE=UPLADE+1.0D0/((ARG**2)*DEXP((ARG*PI/2.0D0)**2*FO(I)))
         UPLADE=UPLADE*8.0D0/(PI**2)
         UCYL=0.0D0
C     WRITE(6,300)
C 300 FORMAT(' DETTE ER F/R L/KKE 2')
         DO 30 J=1,NCYL
   30       UCYL=UCYL+1.0D0/(BETA(J)**2*DEXP(BETA(J)**2*FO(I)))
```

```
          UCYL=UCYL*4.0D0
          UKUGLE=0.0D0
C     WRITE(6,400)
C 400 FORMAT(' DETTE ER F/R L/KKE 3')
          DO 40 J=1,NKUGLE
             ARG=DFLOAT(J)
   40        UKUGLE=UKUGLE+1.0D0/(ARG**2*DEXP((ARG*PI)**2*FO(I)))
          UKUGLE=UKUGLE*6.0D0/(PI**2)
          WRITE(6,50) FO(I),UPLADE,UCYL,UKUGLE,NPLADE,NCYL,NKUGLE
   50     FORMAT(4F9.6,3I7)
   10     CONTINUE
      STOP
      END
```

BILAG 11

NULPUNKTER FOR BESSELFUNKTIONEN AF 0. ORDEN 1. ART

Nulpunkterne β_n er beregnet efter formlen

$$\beta_n = \frac{1}{4}\pi a \left\{ 1 + \frac{2}{\pi^2 a^2} - \frac{62}{3\pi^4 a^4} + \frac{15116}{15\pi^6 a^6} - \frac{12544474}{105\pi^8 a^8} + \frac{8368654292}{315\pi^{10} a^{10}} \right\}$$

$$a = 4n - 1$$

hvor β_n er det n'te nulpunkt for J_o, jvf. CRC Standard Mathematical Tables 26th Edition, p. 402.

n	β_n [CRC]	β_n [formel]
1	2.4048	2.4133
2	5.5201	5.5201
3	8.6537	8.6537
4	11.7915	11.7915
5	14.9309	14.9309
6	18.0711	18.0711
7	21.2116	21.2116
8		24.3525
9		27.4935
10		30.6346
11		33.7758
12		36.9171
13		40.0584
14		43.1998
15		46.3412
16		49.4826
17		52.6241
18		55.7655

Bilag 12 Udskrift fra en kørsel med MEANMOIS

FO	UM PLADE	UM CYLINDER	UM KUGLE	N PLADE	N CYLINDER	N KUGLE
.001500	.956298	.914109	.873394	97	18	96
.002000	.949537	.901104	.854612	84	18	83
.003000	.938196	.879438	.823588	68	18	68
.004000	.928635	.861334	.797905	59	18	59
.005000	.920211	.845507	.775635	53	18	52
.006000	.912596	.831299	.755788	48	18	48
.007000	.905593	.818317	.737779	45	18	44
.008000	.899075	.806307	.721224	42	18	41
.009000	.892953	.795091	.705858	39	18	39
.010000	.887162	.784540	.691486	37	18	37
.015000	.861802	.738996	.630407	31	18	30
.020000	.840423	.701450	.581269	26	18	26
.030000	.804559	.640245	.503677	22	18	21
.040000	.774324	.590416	.442972	19	18	18
.050000	.747687	.547893	.393060	17	17	16
.060000	.723605	.510585	.350814	15	15	15
.070000	.701459	.477254	.314377	14	14	14
.080000	.680846	.447091	.282538	13	13	13
.090000	.661487	.419538	.254458	12	13	12
.100000	.643177	.394189	.229521	12	12	11
.150000	.563050	.291875	.138734	10	10	9
.200000	.495912	.217862	.084504	8	8	8
.300000	.386764	.122036	.031475	7	7	6
.400000	.302118	.068436	.011731	6	6	5
.500000	.236050	.038382	.004372	5	5	5
.600000	.184435	.021526	.001630	5	5	4
.700000	.144107	.012073	.000607	4	4	4
.800000	.112597	.006771	.000226	4	4	4
.900000	.087977	.003798	.000084	4	4	3
1.000000	.068740	.002130	.000031	4	3	3
1.100000	.053710	.001195	.000012	4	3	3
1.200000	.041966	.000670	.000004	3	3	3
1.300000	.032790	.000376	.000002	3	3	3
1.400000	.025620	.000211	.000000	3	3	3
1.500000	.020018	.000118	.000000	3	3	3

Pladetilfældet. Tabel over $(u(r,t)-u_\infty)/(u_o-u_\infty)$ for $0 \le Fo \le 0.5$ med spring på 0.00125.

T	X/L = FO	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
.0000000	.0000000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	.00000
.0003125	.0012500	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	.99998	.99965	.99379	.88854	.00000
.0006250	.0025000	1.00000	1.00000	1.00000	1.00000	1.00000	.99999	.99986	.99814	.97778	.80062	.00000
.0009375	.0037500	1.00000	1.00000	1.00000	1.00000	1.00000	.99996	.99950	.99486	.95626	.73015	.00000
.0012500	.0050000	1.00000	1.00000	1.00000	1.00000	.99999	.99987	.99874	.98969	.93195	.67280	.00000
.0015625	.0062500	1.00000	1.00000	1.00000	1.00000	.99997	.99968	.99747	.98280	.90656	.62543	.00000
.0018750	.0075000	1.00000	1.00000	1.00000	.99999	.99992	.99936	.99560	.97444	.88112	.58576	.00000
.0021875	.0087500	1.00000	1.00000	1.00000	.99998	.99984	.99886	.99311	.96491	.85627	.55211	.00000
.0025000	.0100000	1.00000	1.00000	.99999	.99996	.99970	.99815	.99000	.95447	.83236	.52323	.00000
.0028125	.0112500	1.00000	1.00000	.99999	.99992	.99951	.99720	.98629	.94338	.80958	.49818	.00000
.0031250	.0125000	1.00000	1.00000	.99998	.99987	.99923	.99599	.98202	.93184	.78798	.47623	.00000
.0034375	.0137500	1.00000	.99999	.99996	.99979	.99885	.99451	.97726	.92004	.76759	.45682	.00000
.0037500	.0150000	1.00000	.99999	.99994	.99967	.99837	.99276	.97206	.90810	.74838	.43952	.00000
.0040625	.0162500	.99999	.99998	.99991	.99952	.99777	.99074	.96648	.89614	.73028	.42400	.00000
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.0046875	.0187500	.99999	.99996	.99980	.99908	.99619	.98592	.95440	.87250	.69718	.39722	.00000
.0050000	.0200000	.99998	.99994	.99972	.99878	.99520	.98315	.94800	.86092	.68204	.38558	.00000
.0053125	.0212500	.99997	.99991	.99962	.99842	.99407	.98016	.94143	.84956	.66775	.37488	.00000
.0056250	.0225000	.99995	.99988	.99949	.99799	.99281	.97696	.93473	.83845	.65425	.36502	.00000
.0059375	.0237500	.99993	.99983	.99934	.99750	.99141	.97357	.92794	.82759	.64147	.35589	.00000
.0062500	.0250000	.99990	.99978	.99916	.99693	.98987	.97002	.92107	.81701	.62936	.34740	.00000
.0065625	.0262500	.99987	.99971	.99894	.99629	.98821	.96631	.91417	.80670	.61787	.33949	.00000
.0068750	.0275000	.99982	.99962	.99868	.99557	.98642	.96247	.90725	.79667	.60695	.33209	.00000
.0071875	.0287500	.99977	.99952	.99839	.99478	.98451	.95850	.90034	.78691	.59656	.32516	.00000
.0075000	.0300000	.99970	.99940	.99806	.99391	.98249	.95443	.89344	.77743	.58667	.31864	.00000
.0078125	.0312500	.99962	.99926	.99769	.99296	.98036	.95027	.88659	.76822	.57723	.31249	.00000
.0081250	.0325000	.99952	.99910	.99727	.99194	.97812	.94604	.87978	.75927	.56821	.30668	.00000
.0084375	.0337500	.99941	.99891	.99681	.99084	.97579	.94174	.87303	.75058	.55960	.30119	.00000
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.0100000	.0400000	.99851	.99755	.99380	.98429	.96293	.91961	.84040	.71068	.52157	.27754	.00000
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.0893750	.3575000	.52671	.52024	.50099	.46943	.42631	.37268	.30986	.23937	.16295	.08250	.00000
.0896875	.3587500	.52510	.51865	.49946	.46799	.42500	.37153	.30890	.23863	.16245	.08225	.00000
.0900000	.3600000	.52349	.51706	.49792	.46655	.42369	.37039	.30795	.23789	.16195	.08199	.00000
.0903125	.3612500	.52188	.51547	.49640	.46512	.42239	.36925	.30700	.23716	.16145	.08174	.00000
.0906250	.3625000	.52028	.51389	.49487	.46369	.42109	.36811	.30605	.23642	.16095	.08148	.00000
.0909375	.3637500	.51869	.51231	.49335	.46226	.41979	.36698	.30511	.23569	.16045	.08123	.00000
.0912500	.3650000	.51710	.51074	.49184	.46084	.41850	.36585	.30417	.23497	.15995	.08098	.00000
.0915625	.3662500	.51551	.50918	.49033	.45943	.41721	.36472	.30323	.23424	.15946	.08073	.00000
.0918750	.3675000	.51393	.50761	.48883	.45802	.41593	.36360	.30229	.23352	.15897	.08048	.00000
.0921875	.3687500	.51235	.50606	.48732	.45661	.41465	.36248	.30136	.23280	.15848	.08023	.00000
.0925000	.3700000	.51078	.50451	.48583	.45521	.41338	.36136	.30043	.23208	.15799	.07998	.00000
.0928125	.3712500	.50921	.50296	.48434	.45381	.41211	.36025	.29950	.23136	.15750	.07974	.00000
.0931250	.3725000	.50765	.50141	.48285	.45241	.41084	.35914	.29858	.23065	.15701	.07949	.00000
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.0937500	.3750000	.50454	.49834	.47989	.44964	.40831	.35693	.29674	.22923	.15604	.07900	.00000
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.0950000	.3800000	.49838	.49225	.47403	.44414	.40332	.35256	.29310	.22641	.15413	.07803	.00000
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.0968750	.3875000	.48927	.48326	.46536	.43601	.39593	.34610	.28773	.22225	.15129	.07659	.00000

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.0975000	.3900000	.48628	.48030	.46251	.43334	.39350	.34397	.28596	.22089	.15036	.07612	.00000
.0978125	.3912500	.48478	.47882	.46109	.43201	.39229	.34291	.28508	.22021	.14990	.07589	.00000
.0981250	.3925000	.48330	.47735	.45967	.43068	.39108	.34186	.28420	.21953	.14944	.07565	.00000
.0984375	.3937500	.48181	.47589	.45826	.42936	.38988	.34080	.28332	.21885	.14898	.07542	.00000
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.0990625	.3962500	.47886	.47297	.45545	.42672	.38749	.33871	.28158	.21750	.14806	.07496	.00000
.0993750	.3975000	.47739	.47152	.45405	.42541	.38630	.33767	.28071	.21683	.14760	.07472	.00000
.0996875	.3987500	.47592	.47007	.45266	.42410	.38511	.33663	.27985	.21617	.14715	.07449	.00000
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.1018750	.4075000	.46579	.46006	.44301	.41506	.37690	.32945	.27387	.21155	.14400	.07290	.00000
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.1040625	.4162500	.45587	.45026	.43358	.40622	.36886	.32242	.26803	.20703	.14093	.07134	.00000
.1043750	.4175000	.45447	.44888	.43224	.40497	.36773	.32143	.26720	.20639	.14049	.07112	.00000
.1046875	.4187500	.45308	.44750	.43092	.40373	.36660	.32044	.26638	.20576	.14006	.07090	.00000
.1050000	.4200000	.45168	.44613	.42959	.40249	.36547	.31945	.26556	.20512	.13963	.07069	.00000
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.1065625	.4262500	.44479	.43932	.42304	.39634	.35989	.31457	.26150	.20199	.13749	.06960	.00000
.1068750	.4275000	.44343	.43797	.42174	.39512	.35878	.31360	.26070	.20136	.13707	.06939	.00000
.1071875	.4287500	.44206	.43662	.42044	.39391	.35768	.31264	.25989	.20074	.13665	.06918	.00000
.1075000	.4300000	.44071	.43528	.41915	.39270	.35658	.31168	.25909	.20013	.13623	.06896	.00000
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.1084375	.4337500	.43666	.43128	.41530	.38909	.35330	.30881	.25671	.19829	.13497	.06833	.00000
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.1090625	.4362500	.43398	.42864	.41275	.38670	.35113	.30691	.25513	.19707	.13414	.06791	.00000
.1093750	.4375000	.43265	.42732	.41148	.38551	.35005	.30597	.25435	.19646	.13373	.06770	.00000
.1096875	.4387500	.43132	.42601	.41022	.38433	.34898	.30503	.25357	.19586	.13332	.06749	.00000
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.1109375	.4437500	.42604	.42080	.40520	.37963	.34470	.30129	.25046	.19346	.13168	.06666	.00000

.1112500	.4450000	.42473	.41951	.40395	.37846	.34365	.30037	.24969	.19286	.13128	.06646	.00000
.1115625	.4462500	.42343	.41822	.40271	.37730	.34259	.29944	.24892	.19227	.13087	.06625	.00000
.1118750	.4475000	.42213	.41693	.40148	.37614	.34154	.29852	.24816	.19168	.13047	.06605	.00000
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.1134375	.4537500	.41568	.41057	.39535	.37039	.33632	.29396	.24437	.18875	.12848	.06504	.00000
.1137500	.4550000	.41441	.40931	.39413	.36925	.33529	.29306	.24361	.18817	.12808	.06484	.00000
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.1181250	.4725000	.39694	.39205	.37751	.35368	.32114	.28070	.23333	.18022	.12268	.06210	.00000
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.1206250	.4825000	.38728	.38252	.36833	.34508	.31333	.27387	.22766	.17584	.11969	.06059	.00000
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.1218750	.4875000	.38255	.37784	.36383	.34086	.30950	.27051	.22487	.17369	.11822	.05985	.00000
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.1243750	.4975000	.37324	.36865	.35498	.33257	.30197	.26393	.21940	.16946	.11535	.05839	.00000
.1246875	.4987500	.37210	.36752	.35389	.33155	.30104	.26312	.21872	.16894	.11499	.05821	.00000
.1250000	.5000000	.37095	.36639	.35280	.33053	.30012	.26231	.21805	.16842	.11464	.05803	.00000

Pladetilfældet. Tabel over $(u(r,t)-u_{\infty})/(u_{o}-u_{\infty})$ for $0 \leq Fo \leq 1.5$ med spring i Fo på 0.01.

	X/L =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
T	FO											
.0000000	.0000000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	.00000
.0025000	.0100000	.99999	.99998	.99995	.99980	.99926	.99724	.98969	.96152	.85641	.46410	.00000
.0050000	.0200000	.99991	.99984	.99951	.99840	.99487	.98405	.95238	.86672	.66838	.38120	.00000
.0075000	.0300000	.99951	.99919	.99782	.99385	.98320	.95651	.89559	.77510	.58403	.31310	.00000
.0100000	.0400000	.99826	.99734	.99377	.98469	.96397	.92082	.84051	.70962	.51835	.27560	.00000
.0125000	.0500000	.99544	.99354	.98668	.97117	.94026	.88436	.79268	.65594	.47220	.24764	.00000
.0150000	.0600000	.99042	.98730	.97666	.95464	.91495	.84965	.75070	.61286	.43586	.22702	.00000
.0175000	.0700000	.98293	.97855	.96421	.93633	.88949	.81733	.71419	.57690	.40687	.21068	.00000
.0200000	.0800000	.97303	.96750	.94985	.91703	.86457	.78758	.68208	.54650	.38288	.19744	.00000
.0225000	.0900000	.96099	.95449	.93407	.89725	.84052	.76020	.65365	.52032	.36266	.18639	.00000
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.0275000	.1100000	.93193	.92399	.89964	.85740	.79531	.71157	.60531	.47724	.33014	.16886	.00000
.0300000	.1200000	.91559	.90718	.88156	.83765	.77410	.68979	.58444	.45916	.31674	.16172	.00000
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.0350000	.1400000	.88071	.87173	.84462	.79892	.73416	.65019	.54757	.42789	.29394	.14968	.00000
.0375000	.1500000	.86262	.85350	.82605	.78003	.71529	.63202	.53107	.41416	.28406	.14450	.00000
.0400000	.1600000	.84431	.83513	.80754	.76149	.69707	.61476	.51559	.40142	.27496	.13975	.00000
.0425000	.1700000	.82593	.81674	.78916	.74331	.67946	.59828	.50099	.38951	.26651	.13537	.00000
.0450000	.1800000	.80758	.79842	.77099	.72550	.66240	.58250	.48715	.37832	.25862	.13128	.00000
.0475000	.1900000	.78933	.78024	.75306	.70808	.64586	.56734	.47397	.36774	.25120	.12745	.00000
.0500000	.2000000	.77125	.76226	.73540	.69103	.62980	.55275	.46138	.35768	.24418	.12384	.00000
.0525000	.2100000	.75339	.74452	.71804	.67436	.61420	.53867	.44930	.34809	.23751	.12042	.00000
.0550000	.2200000	.73579	.72705	.70100	.65807	.59904	.52506	.43768	.33891	.23115	.11716	.00000
.0575000	.2300000	.71847	.70989	.68429	.64216	.58429	.51187	.42648	.33009	.22505	.11405	.00000
.0600000	.2400000	.70146	.69304	.66792	.62661	.56993	.49909	.41566	.32160	.21920	.11106	.00000
.0625000	.2500000	.68478	.67651	.65190	.61143	.55595	.48669	.40520	.31341	.21357	.10819	.00000
.0650000	.2600000	.66842	.66033	.63622	.59660	.54234	.47464	.39505	.30549	.20813	.10542	.00000
.0675000	.2700000	.65241	.64448	.62088	.58213	.52907	.46292	.38521	.29782	.20287	.10275	.00000
.0700000	.2800000	.63673	.62898	.60590	.56800	.51614	.45152	.37566	.29038	.19778	.10016	.00000
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.0750000	.3000000	.60641	.59900	.57694	.54075	.49125	.42963	.35734	.27615	.18805	.09522	.00000
.0775000	.3100000	.59176	.58452	.56297	.52761	.47927	.41910	.34855	.26933	.18339	.09286	.00000
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