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Numerical Simulation of Building Components : Towards an Efficient Implementation of Air Convection in HAM-models

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‘Low energy building’, built in 2009

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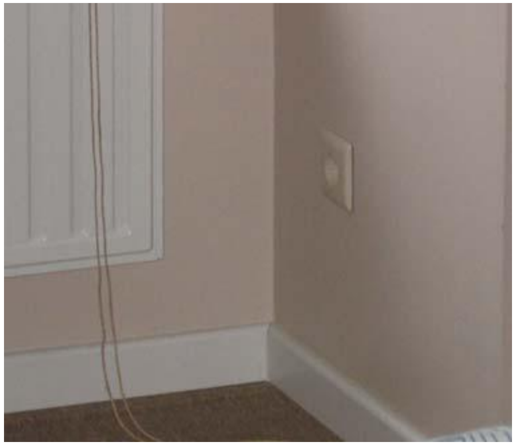
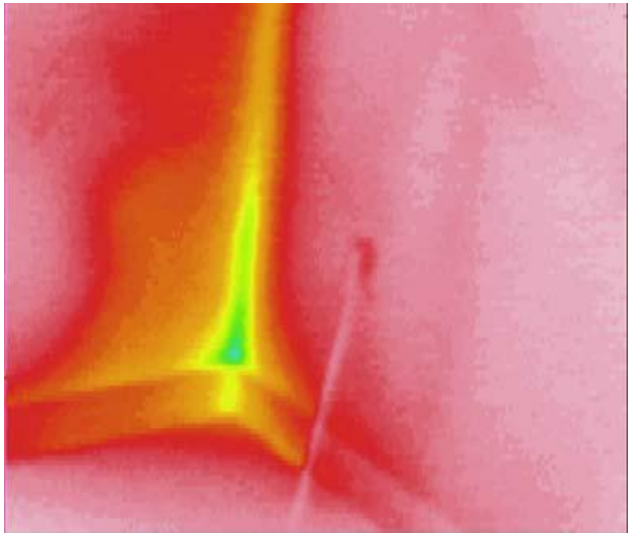
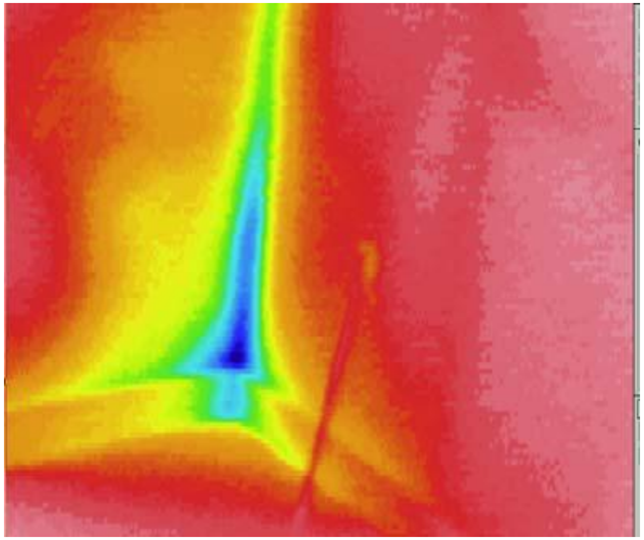




No pressure



Under pressure

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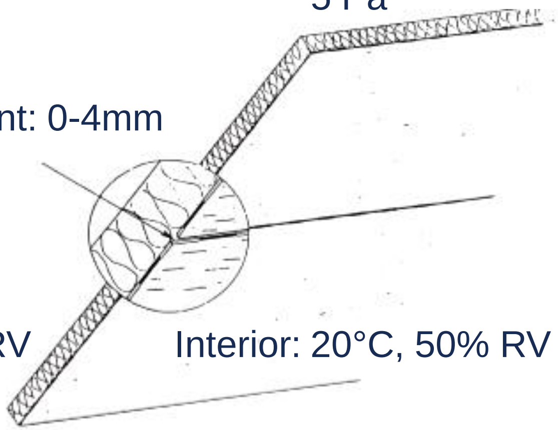

5 Pa

Tongue and groove joint: 0-4mm

Exterior: -10°C, 80% RV

Interior: 20°C, 50% RV

CONVECTION VS DIFFUSION

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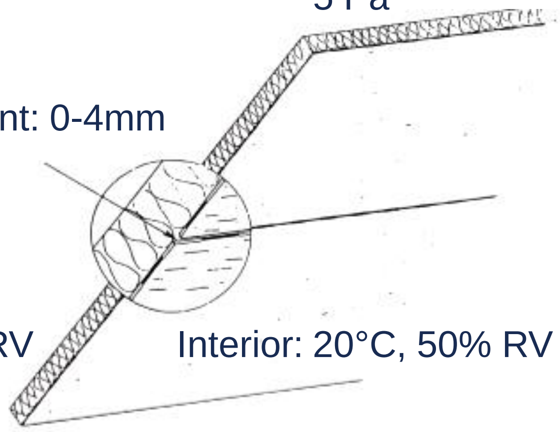

5 Pa

Tongue and groove joint: 0-4mm

Exterior: -10°C, 80% RV

Interior: 20°C, 50% RV

	DIFFUSION		
Vapour diffusion resistance	µd=100m	µd=50m	µd=3
Daily diffusion transport (g/m²)	0,15	0,3	5

	CONVECTION		
Joint (mm)	0mm	2mm	4mm
Daily convection transport (g/m)	9	39	144

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Photo: R. Borsch-Laaks, 2009

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HAM-models including air transport are scare

→ Efficient implementation of air convection in HAM-models

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Model equations

H

$$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_v j^v_{diff} + h_w j^w\right]_k + \Sigma \dot{u}$$

A

M

$$\frac{\partial \rho^{w+v}}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^v_{diff} + j^w\right]_k$$

Model equations

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H $$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_v\left(j^v_{diff} + j^v_{conv}\right) + h_w j^w + h_a j^a\right]_k + \Sigma\dot{u}$$

A $$\boxed{\frac{\partial \rho^a}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^a\right]_k}$$

M $$\frac{\partial \rho^{w+v}}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^v_{diff} + j^v_{conv} + j^w\right]_k$$

Model equations

H $$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + \left(h_v\left(j^v_{diff} + j^v_{conv}\right) + h_w j^w\right) + h_a j^a\right]_k + \Sigma\dot{u}$$

A $$\frac{\partial \rho^a}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^a\right]_k$$

$$\left(\textbf{M} \qquad \frac{\partial \rho^{w+v}}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^v_{diff} + j^v_{conv} + j^w\right]_k\right)$$

Model equations

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H $$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma \dot{u}$$

A $$\frac{\partial \rho^a}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^a\right]_k$$

$$j^a = -\rho_a \frac{k_a}{\eta}\left(\frac{\partial p_a}{\partial x_k} + \rho_a g \cos\alpha\right)$$

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Previous attempts/approaches

Previous attempts

Fully coupled approach (Delphin 4)

$$\frac{\partial \rho^{a}}{\partial t} = -\frac{\partial}{\partial x_k}\left[j^{a}\right]_k$$

$$\left(c_m \rho_b + c_a \rho_a\right)\frac{\partial T}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_a j^{a}\right]_k + \Sigma \dot{u}$$

Previous attempts

Fully coupled

$$\frac{\partial P_a}{\partial t} = \enclose{circle}{\frac{k_a}{c_a}} \nabla^2 P_a$$

$$\frac{\partial T}{\partial t} = \enclose{circle}{\frac{\lambda}{\rho c}} \nabla^2 T$$

Previous attempts

Fully coupled

6.8 m²/s

$$\frac{\partial P_a}{\partial t} = \boxed{\frac{k_a}{c_a}} \nabla^2 P_a$$

1.1 10⁻⁶ m²/s

$$\frac{\partial T}{\partial t} = \boxed{\frac{\lambda}{\rho c}} \nabla^2 T$$

Example for rock wool*

c_a=1,2.10^{-5} kg/m^3.Pa
k_a=8.10^{-5} s

ρc= 33600 J/K.m^3
λ=0.036 W/mK

* H. Hens, Heat and Mass transport, 2003

Previous attempts

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Fully coupled

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$$\frac{\partial P_a}{\partial t} = \boxed{\frac{k_a}{c_a}} \nabla^2 P_a$$

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Example for rock wool*

c_a=1,2.10^{-5} kg/m^3.Pa
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ρc= 33600 J/K.m^3
λ=0.036 W/mK

➡ > 6 000 000

* H. Hens, Heat and Mass transport, 2003

Previous attempts

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Quasi steady state approach (Delphin 5)

$$\cancel{\frac{\partial \rho^a}{\partial t}} = -\frac{\partial}{\partial x_k}\left[j^a\right]_k$$

$$(c_m \rho_b + c_a \rho_a)\frac{\partial T}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma \dot{u}$$

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Quasi steady state approach

$$0 = -\frac{\partial}{\partial x_k}\left[j^a\right]_k$$

$$\left(c_m \rho_b + c_a \rho_a\right)\frac{\partial T}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma \dot{u}$$

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Quasi steady state approach

$$
\text{DAE}\begin{cases}
0 = -\dfrac{\partial}{\partial x_k}\left[j^a\right]_k \\[2ex]
\left(c_m\rho_b + c_a\rho_a\right)\dfrac{\partial T}{\partial t} = -\dfrac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma\dot{u}
\end{cases}
$$

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Previous attempts

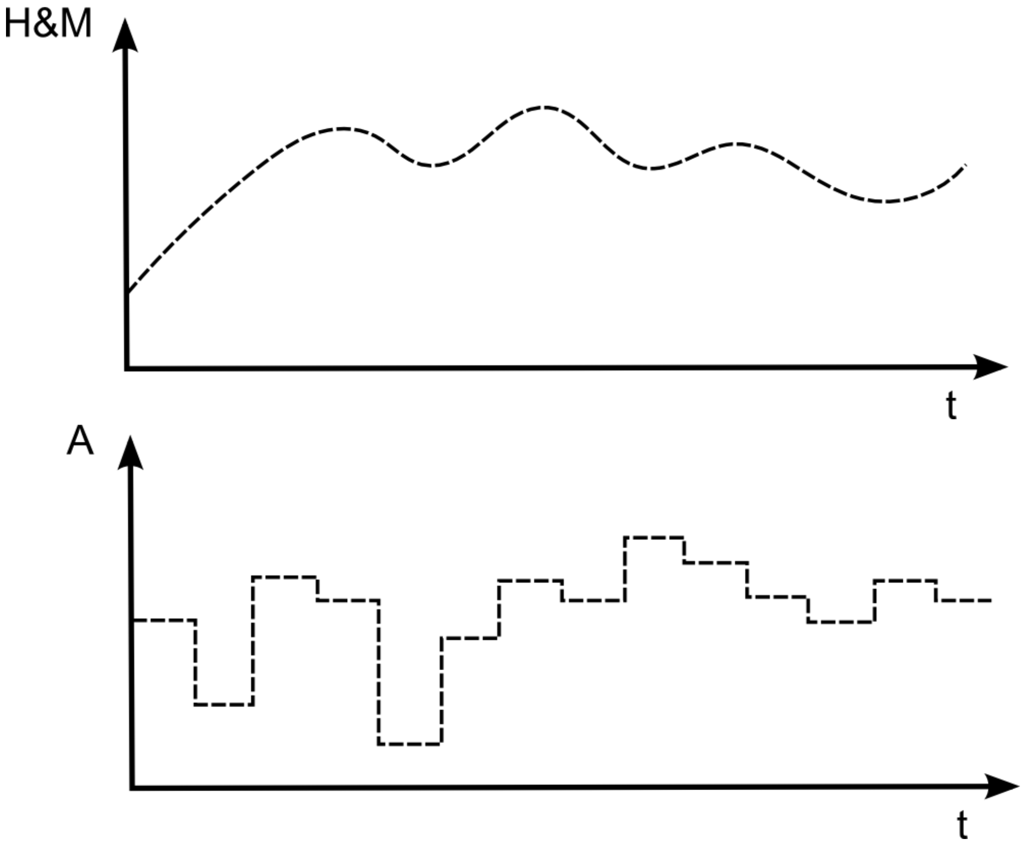
Quasi steady state approach

$$\text{DAE}\begin{cases} 0 = -\dfrac{\partial}{\partial x_k}\left[j^a\right]_k \\ \left(c_m \rho_b + c_a \rho_a\right)\dfrac{\partial T}{\partial t} = -\dfrac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma \dot{u} \end{cases}$$

General form of the ODE integrator: $\dot{y} = f(t, y)$

Previous attempts

Quasi steady state



Previous attempts

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Quasi steady state

- Good simulation performance
- Perfect solution for forced convection problems
- Might lead to numerical instability for buoyant dominated problems

Model

Governing equations

$$0 = -\frac{\partial}{\partial x_k}\left[j^a\right]_k$$

$$\left(c_m \rho_b + c_a \rho_a\right)\frac{\partial T}{\partial t} = -\frac{\partial}{\partial x_k}\left[q_{cond} + h_a j^a\right]_k + \Sigma \dot{u}$$

Transport equations

$$j^a = -\rho_a \frac{k_a}{\eta}\left(\frac{\partial p_a}{\partial x_k} + \rho_a g \cos\alpha\right)$$

$$q_{cond} = -\lambda \frac{\partial T}{\partial x}$$

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Numerical solution method

Finite Volume Method (FVM)

↳ System PDE transformed to DAE

Discretization:

Diffusion terms: central-difference

$$(q_{cond})_{L,i} = -\lambda_{L,i} \frac{T_i - T_{i-1}}{0.5\left(\Delta x_{i-1} + \Delta x_i\right)}$$

Convective terms: upwind scheme

$$(h_a j^a)_{L,i} = \begin{cases} (h_a)_{i-1} j^a & j^a > 0 \\ (h_a)_i j^a & j^a \le 0 \end{cases}$$

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$$F(t, y, \dot{y}) = 0$$

$$y = [p_{a,0}, u_0, p_{a,1}, u_1, \ldots, p_{a,n}, u_n]^T$$

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Numerical solution method

$$F(t, y, \dot{y}) = 0$$

$$y = [p_{a,0},\ u_0,\ p_{a,1},\ u_1, \ldots,\ p_{a,n},\ u_n]^T$$

DAE-solver: IDA sundials

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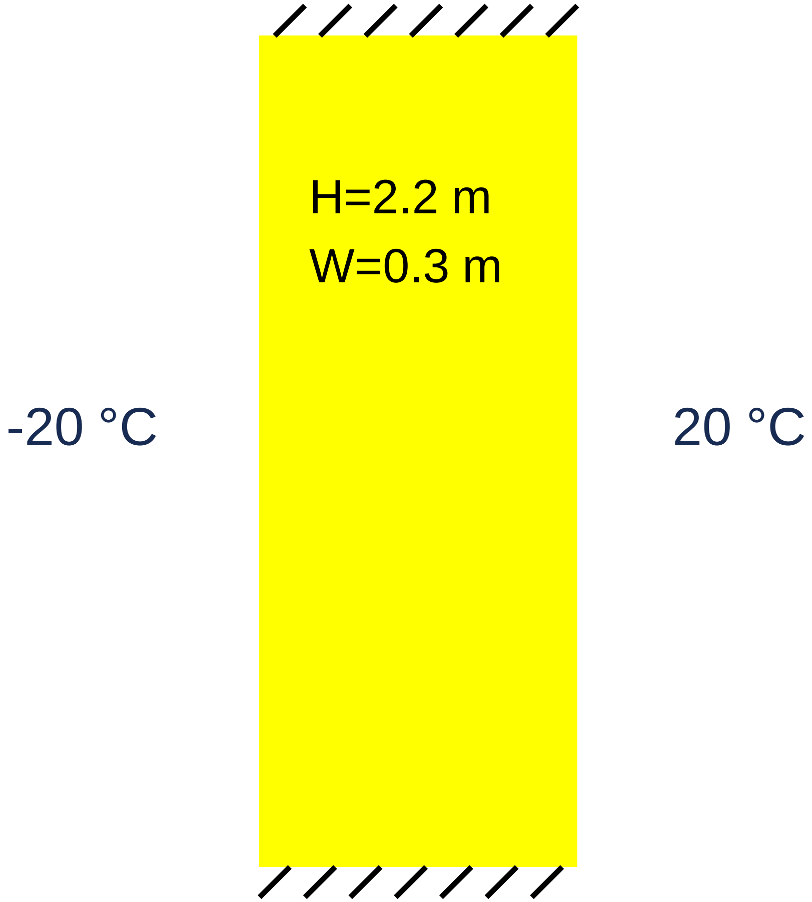
Natural convection in a porous media: vertical / horizontal layer

Kohonen, 1985



H=2.2 m
W=0.3 m

-20 °C

20 °C

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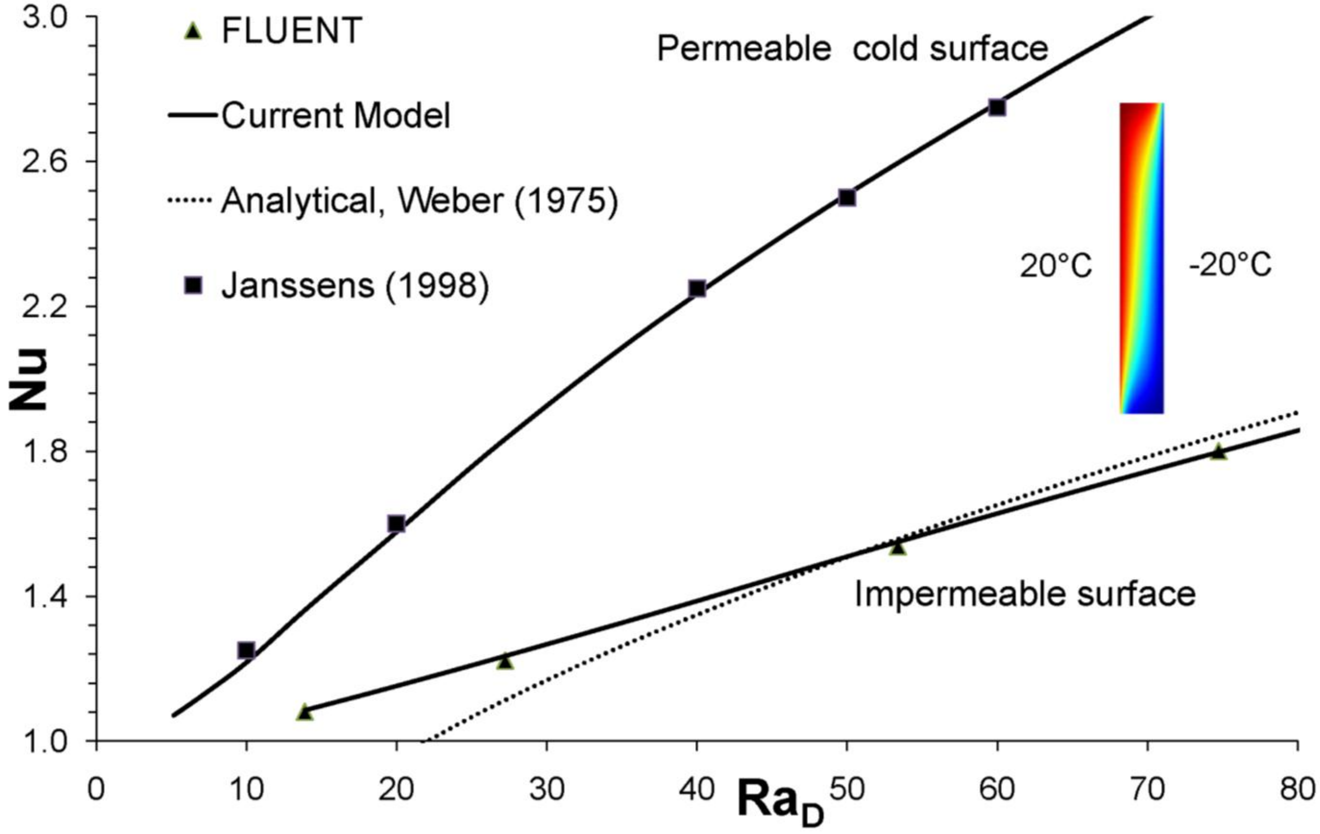
$$Nu = \frac{Q_{tot}}{Q_{cond}} = \frac{Q_{tot}}{H \Delta T \lambda_x / D}$$

$$Ra_D = g \beta D \Delta T \left(\frac{\rho c}{v} \right) \frac{k_x}{\lambda_x} \frac{4 a_k}{\left(\sqrt{a_\lambda} + \sqrt{a_k} \right)^2}$$

Validation

Vertical Layer



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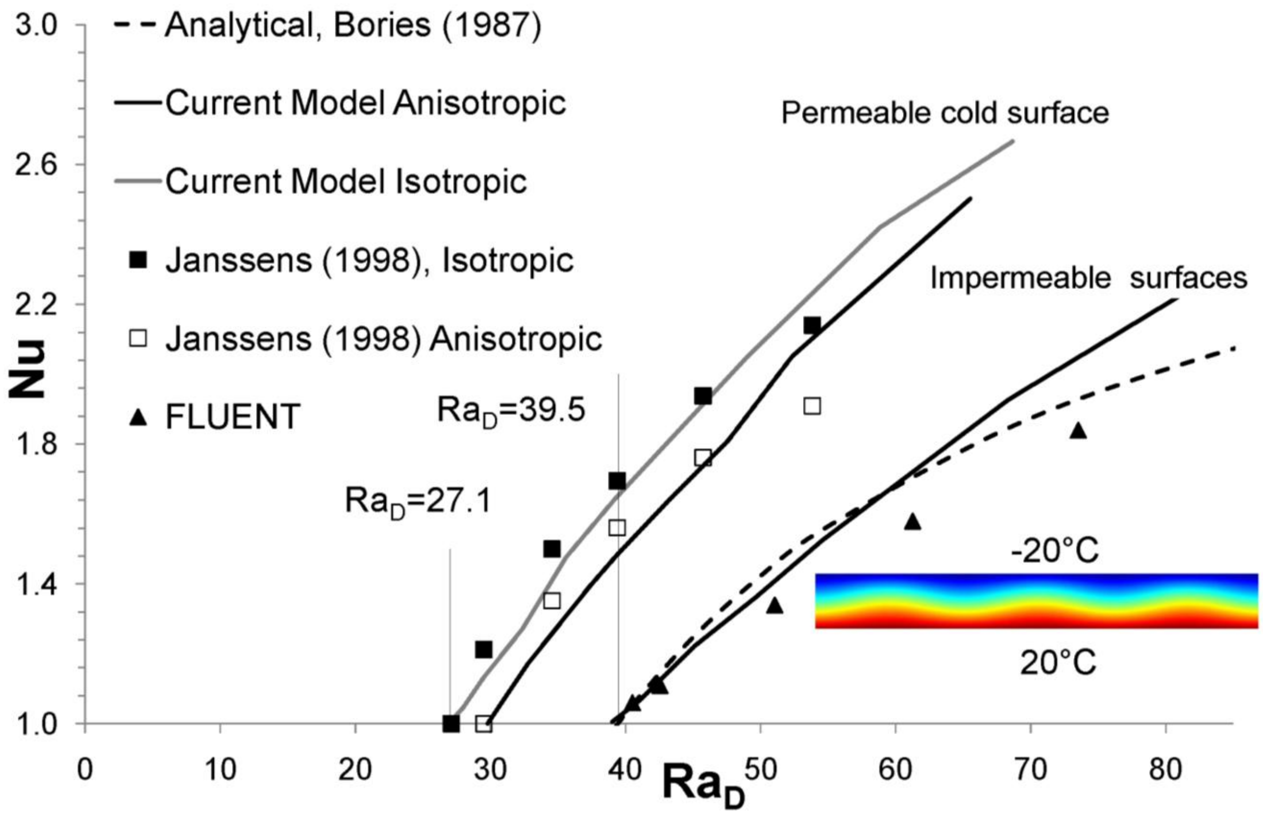
Horizontal Layer



Conclusions

- Implementation of air transport in Delphin HAM tool
- Previous approaches were discussed
- A new approaches using DAE solver
- Validation