LECTURE N° 10

- Design and Analysis Tools-

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FOR A SUSTAINABLE FUTURE

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Lecture contributions

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HEATING SYSTEM - HYDRAULIC CALCULATION

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Basic equations

Transmitted output Q (W=J/s)

$$Q = M \cdot c \cdot \Delta\Theta$$

Design flowrate M (kg/s)

$$M = \frac{Q}{c \cdot \Delta\Theta}$$

Velocity from continuity equation w (m/s)

$$w = \frac{V}{S} = \frac{M}{\rho \cdot \frac{\pi \cdot d^2}{4}}$$

Pipe diameter d (m)

$$d = \sqrt{\frac{4 \cdot M}{\pi \cdot \rho \cdot w}}$$

1kWh = 3,6 x 10^6 J

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Pressure losses

Pressure losses Δp_L = friction Δp_{FL} + local resistance Δp_{RL}

$$\Delta p_L = \Delta p_{FL} + \Delta p_{RL}$$

<u>Friction</u>

$$\Delta p_{FL} = \frac{\lambda}{d} \cdot \rho \cdot \frac{w^2}{2} \cdot l$$

<u>Friction coefficient λ</u>

- Laminar flow $\lambda = \frac{64}{\mathrm{Re}}$
- Transient $\lambda = \lambda_{2320} + \frac{\lambda_{4000} - \lambda_{2320}}{4000 - 2320} \cdot (\mathrm{Re} - 2320)$
- Turbulent flow $\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{2.51}{\mathrm{Re} \cdot \sqrt{\lambda}} + \frac{k}{3.71 \cdot d} \right)$

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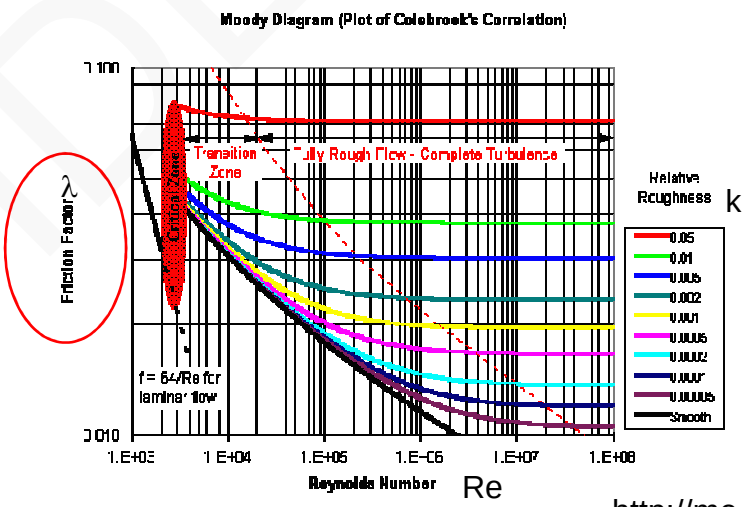
Pressure losses in pipes



http://me.queensu.ca

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Pressure losses

- Local resistance

$$\Delta p_{RL} = \zeta \cdot \frac{w^2}{2} \cdot \rho$$

- Coefficient ζ – fittings - elbows, valves, T-shape…

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Two pipes system

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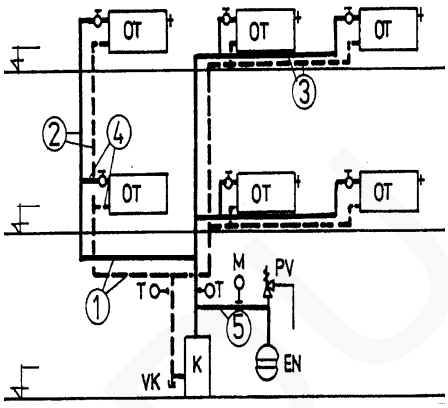
Hydronic system calculation

- Temp difference setup
- Transferred output
- Circulation mode
- Hydraulic scheme, sections, circuits
- Water flow rate



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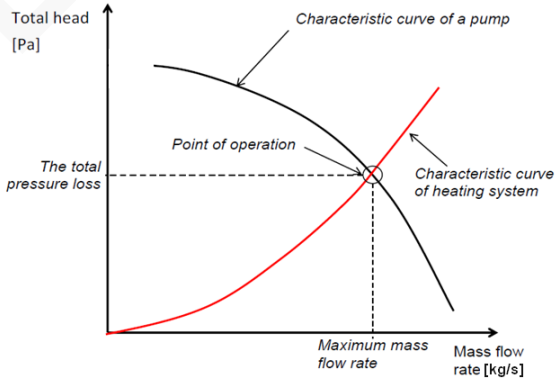
Pump design

- pump head (Pa) $\Delta p = \Delta p_L$
- Flow rate (kg/s) $m_p = M$



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A. Proposal dimensions - a method of given pressure

disposition pressure(Pa)

The share of local resistance to the total loss (Pa / m)

$$R_p = \frac{\Delta p \cdot (1-a)}{\sum l}$$

$$a = \frac{\sum Z}{\sum (R \cdot l + Z)}$$

Circuit length (m)

Type of system	a
exterior wiring	0,1 - 0,2
Heating systems (HS)in large buildings	0,2 - 0,3
Common HS in residential buildings	0,3 - 0,4
HS in old buildings after reconstruction	0,4 - 0,55

– Given pressure→ specific pressure drop R (estimation of *a*) + mass flow → duct diameters

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A. Design dimensions - a method of optimal velocity

– Choice of velocity+ mass flow rate→ duct diameters

Pipe network	w (m/s)
residential buildings - connections to heat emitters , risers	0,3 - 0,7
residential buildings - the horizontal distribution in technical areas	0,8 - 1,5
residential building - outdoor wiring of district heating	2,0 - 3,0
Industrial buildings - connections to heat emitters , risers	0,8 - 2,0
Industrial facilities - outdoor wiring of district heating	2,0 - 3,0

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A. Design dimensions - economic pressure gradient method

- Choice of R (Pa/m) + mass flow rate → duct diameters

Pipe network	w (m/s)	R_{EK} (Pa/m)
residential buildings - connections to heat emitters , risers	0,3 - 0,7	60 - 110
residential buildings - the horizontal distribution in technical areas	0,8 - 1,5	110 - 200
residential building - outdoor wiring of district heating	2,0 - 3,0	200 - 400
Industrial buildings - connections to heat emitters , risers	0,8 - 2,0	110 - 250
Industrial facilities - outdoor wiring of district heating	2,0 - 3,0	200 - 400

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A. Duct dimension design

summary

- Gravity circulation
  - given pressure method
    - effective pressure + additional buoyancy
    - onfloor system?
- Forced circulation
  - *economic pressure gradient* method
    - 60 to 200 Pa.m^{-1}
  - *optimal velocity* method
    - 0.05 to 1.0 m.s-1 (!!! Noise)
  - *given pressure* method
    - pump + extra buoyancy, 10-70 kPa

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B. Control valves settings for steady state

Calculation of pressure loss for the proposed pipe dimension

- Friction
- Local resistances

Pressure loss of the circuit layout compared with the disposition pressure

(natural circulation x forced circulation)

The pressure excess is regulated by control valves settings	The lack of pressure either by increase of the pressure or decrease pressure loss

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B. Control valves settings for steady state

- Control valves for radiators
  - in most cases
- Control valves in the circuit
  - in large systems where it is necessary to compensate for multiple objects or parts
- Chokes in the pipeline
  - not recommended (ingrown, corrosion)

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B. Control valves settings for steady state

$$k_v = \frac{V}{\sqrt{\Delta p}}$$

- ***k_v, k_{vs} value***
- The flow rate in $m^3.h^{-1}$ through control valve with unit pressure difference *Δp=1bar=100kPa*
- used to select control valves presetting
- From given flow V and desired pressure drop Δp I shall establish the k_v value of the armature

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B. Control valves settings for steady state

Example:

â ***We are looking for the setting of the valve of radiator with a 1580W output and gauge pressure of 0.1 bar = 10 kPa***

$$V = \frac{Q \cdot 3600}{c \cdot \Delta t \cdot \rho} = \frac{1580 \cdot 3600}{4196 \cdot 20 \cdot 970} = 0{,}070\left[m^3 \cdot h^{-1}\right]$$

$$k_v = \frac{V}{\sqrt{\Delta p}} = \frac{0{,}070}{\sqrt{0{,}10}} = 0{,}22\left[m^3 \cdot h^{-1}\right]$$

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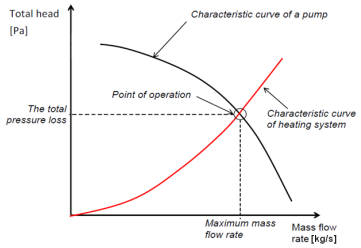
B. Control valves settings for steady state

- Mass flow rate + transport pressure
- Determination of the pump power P (W)

$$P = \frac{\Delta p \cdot V}{\eta}$$



V – flow rate (m^3/s)

Pump efficiency η(-)

!!! Transport pressure (Pa) x allowed gauge pressure!!!

1m w.c.=10 kPa

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Hydraulic stability - balancing

- Why ?
- In the calculation we consider steady state x variable reality mainly caused by:
  - a variable additional buoyancy due to the changing temperature of heating water
  - varying pressure ratios in HS due to the function of thermostatic valves
- Solution:
  - passive controlling by accurate calculation
  - application of automatic control devices

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Hydraulic stability - balancing

- Passive – by the calculation
  - rules for the design of individual parts of HS
  - E.g. for systems with gravity circulation::
    - consume the most pressure on heat emitters
    - pressure drop in the riser = effective pressure merged in the riser
    - pressure loss in horizontal distribution systems = effective pressure merged in horizontal distribution systems
  - numerically difficult, the problem of realization

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Hydraulic stability - balancing

- Applications of automatic control devices
  - bypass valves
    - opens with variations according to the differential pressure, placed to bypass of the pump or between the supply and return piping of HS
    - differential pressure regulators
    - strangling (!) valve in the pipe controlled by differential pressure
    - pump with controlled speed
    - Constant pump pressure within variable flow

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One pipe heating systems

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One pipe heating systems

- Calculation
  - Temperature - Determines temperatures in individual heat emitters under computational conditions
  - Hydraulic - defines the set of valves, pipe dimensions and parameters of the pump

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One pipe heating systems calculations - *Inputs*

- The division into areas, circulation way, connection (mixing, riding)
- Circuit heat output Q_o [W]
- Circuit temperature gradient δt_o [K] *(10-15 K)*
- Coefficient of leaking into the heat emitter α [-] *(0,3-0,5)*

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One pipe heating systems calculations - *temperature calculation*

$$M_T = \alpha_T \cdot M_o$$

Element mass flow rate

$$\delta t_T = \frac{Q_T}{c \cdot M_o \cdot \alpha_T} = \frac{Q_T}{c \cdot M_T}$$

Temperature drop

$$\theta = \frac{\delta t_o}{Q_o}$$

Gradient per unit of output

$$t_{mT} = t_1 - \theta \cdot \sum Q_i - 0{,}5 \cdot \frac{Q_T}{c \cdot M_T}$$

Mean body temperature

$$\Delta t = t_{mT} - t_i$$

The temperature difference between the mean temperature of the radiator and the resulting room temperature Δt

$$Q_N = Q_T \cdot \left(\frac{\Delta t}{\Delta t_N}\right)^{-m} = Q_T \cdot \left(\frac{\Delta t}{60}\right)^{-m}$$

The conversion of nominal to real radiator output

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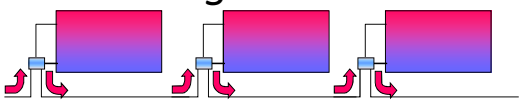
One pipe heating systems calculation-

hydraulic calculation of the system with mixing valves



1. Circuit mass flow M_o

$$M_o = \frac{Q_o}{c \cdot \delta t_o}$$

2. Pipe profile design(according to R or v)

3. Local resistance loss expressed by the equivalent length l_{ekv}

$$l_{ekv} = \sum \xi \cdot \frac{d}{\lambda}$$

4. Computational circuit length L

$$L = l + l_{ekv}$$

5. Circuit pressure loss Δp_c,
n – number of heat emitters, Δp_u, - pressure loss of the node of heat emitter

$$\Delta p_o = L \cdot R + n \cdot \Delta p_u$$

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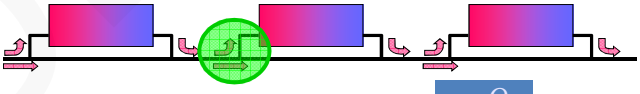
One pipe heating systems calculation-

hydraulic calculation of the system with riding connection



Conversion factor *n:*

- The ratio of diameter of connection pipe - d and core pipeline D
- ε inserted ressistance factor

$$n = \frac{Q_o}{Q_{OT}}$$

$$\frac{d}{D} = \frac{\sqrt[4]{\varepsilon}}{\sqrt{n \cdot \frac{\Delta t_{OT}}{\delta t_o} - 1}}$$

Balance of the short-circuit and the heat emitter:

$$\Delta p_{OT} = \Delta p_D$$

$$\xi_{OT} \cdot \frac{w_{OT}^2}{2} \cdot \rho = \xi_D \cdot \frac{w_D^2}{2} \cdot \rho$$

$$\varepsilon = \frac{\xi_{OT}}{\xi_D} = \frac{w_D^2}{w_{OT}^2} = \frac{M_{OT}^2 \cdot D^4}{M_D^2 \cdot d^4}$$

$$\varepsilon = \frac{M_{OT}^2}{(M_o - M_{OT})^2} \cdot \frac{D^4}{d^4}$$

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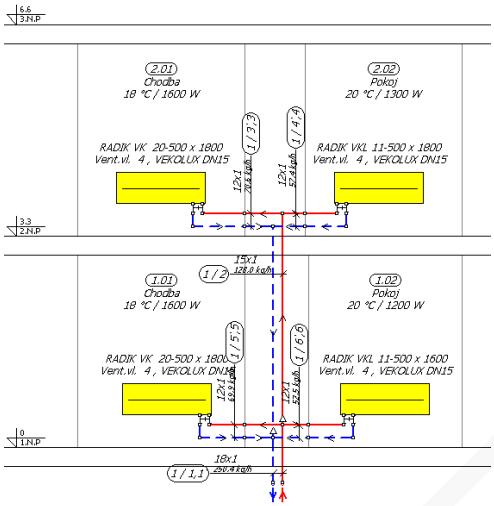
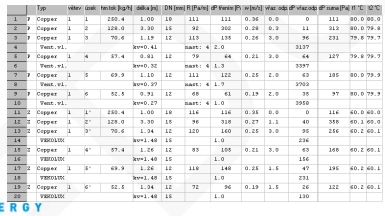
Calculation tools



- Edit speed
- List of material
- Detailed properties
- Graphic interface



		Typ	větev	úsek	hm.tok [kg/h]	délka [m]	DN [mm]	R [Pa/m]	dP třením [P	w [m/s]	vřaz. odp.	dP vřaz.odp	dP suma [Pa]	t1 °C	t2 °C
1	P	Copper	1	1	250.4	1.00	18	111	111	0.36	0.0	0	111	80.0	80.0
2	P	Copper	1	2	128.0	3.30	15	92	302	0.28	0.3	11	313	80.0	79.8
3	P	Copper	1	3	70.6	1.19	12	113	135	0.26	3.0	96	231	79.8	79.7
4		Vent.vl.				kv=0.41		nast: 4	2.0			3137			
5	P	Copper	1	4	57.4	0.81	12	79	64	0.21	3.0	64	127	79.8	79.7
6		Vent.vl.				kv=0.32		nast: 4	1.3			3397			
7	P	Copper	1	5	69.9	1.10	12	111	122	0.25	2.0	63	185	80.0	79.9
8		Vent.vl.				kv=0.37		nast: 4	1.7			3703			
9	P	Copper	1	6	52.5	0.91	12	68	61	0.19	2.0	35	97	80.0	79.9
10		Vent.vl.				kv=0.27		nast: 4	1.0			3958			
11	Z	Copper	1	1'	250.4	1.00	18	116	116	0.35	0.0	0	116	60.0	60.0
12	Z	Copper	1	2'	128.0	3.30	15	96	318	0.27	1.1	40	358	60.1	60.0
13	Z	Copper	1	3'	70.6	1.34	12	120	160	0.25	3.0	95	256	60.2	60.1
14		VEKOLUX				kv=1.48	15		1.0			236			
15	Z	Copper	1	4'	57.4	1.26	12	83	105	0.21	3.0	63	168	60.2	60.1
16		VEKOLUX				kv=1.48	15		1.0			156			
17	Z	Copper	1	5'	69.9	1.26	12	118	148	0.25	1.5	47	195	60.2	60.1
18		VEKOLUX				kv=1.48	15		1.0			231			
19	Z	Copper	1	6'	52.5	1.34	12	72	96	0.19	1.5	26	122	60.2	60.1
20		VEKOLUX				kv=1.48	15		1.0			130			

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Calculation tools

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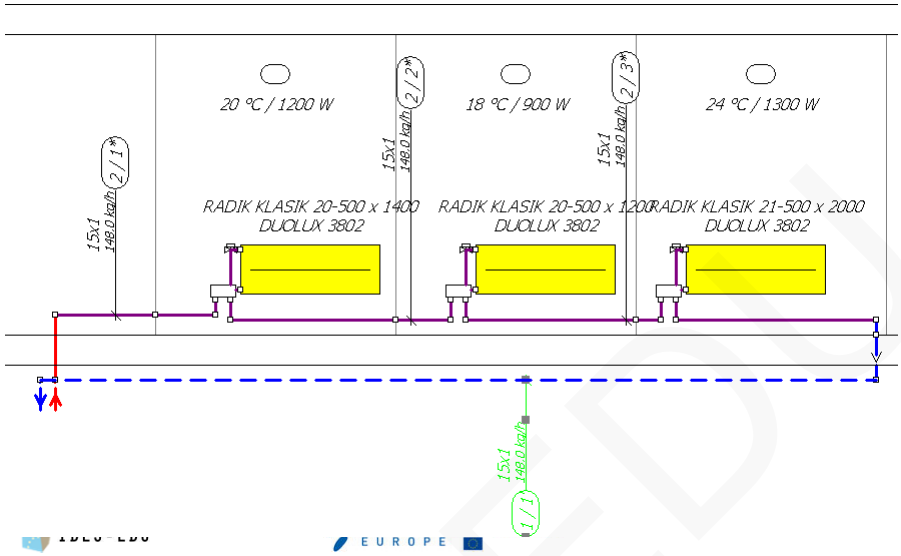
One pipe system calculation



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MODELING AND SIMULATION

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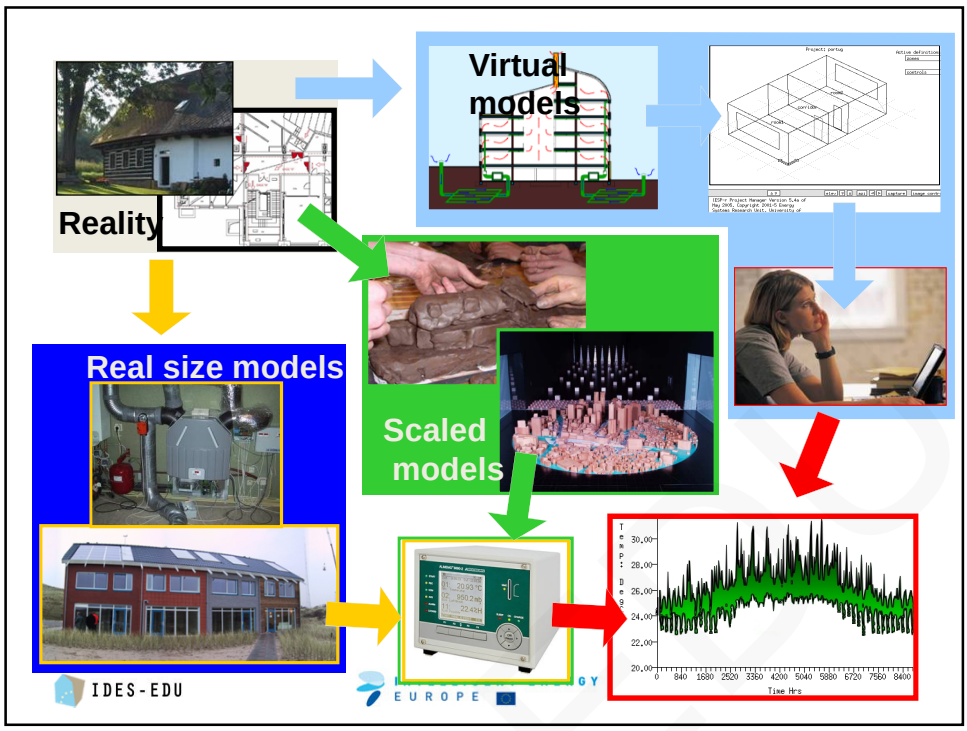
Virtual models
Reality
Real size models
Scaled models
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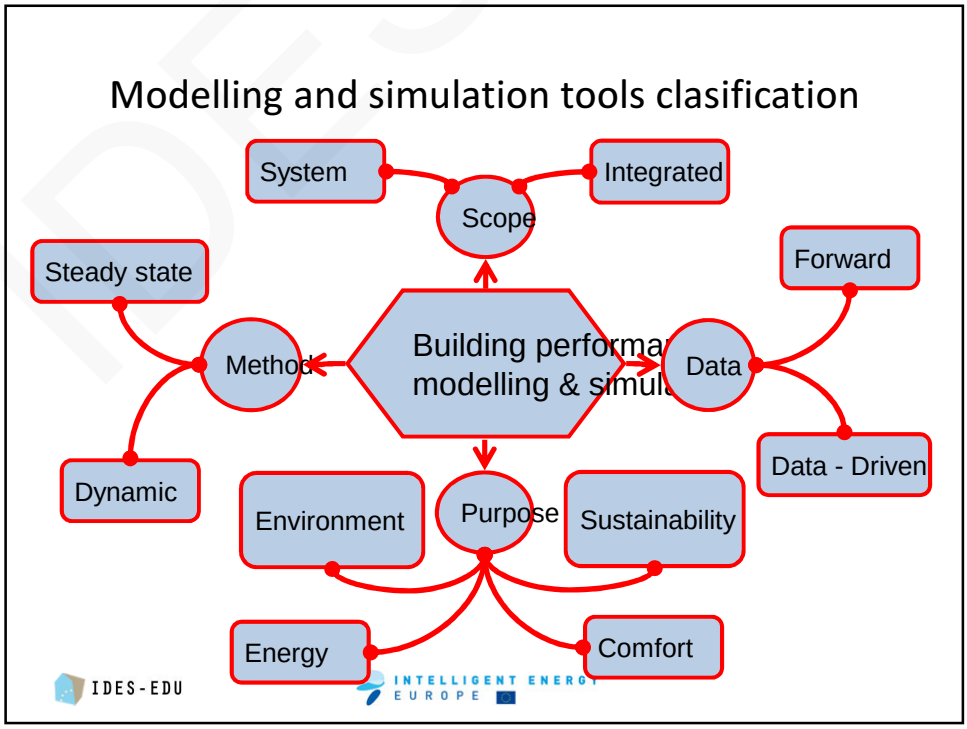
Modelling and simulation tools clasification
System
Integrated
Scope
Steady state
Forward
Method
Building performa
modelling & simul
Data
Data - Driven
Dynamic
Environment
Purpose
Sustainability
Energy
Comfort
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Steady – state methods

Forward

- Modified degree-day method
  - Based on fixed reference temperature of 18.3°C.
- Variable-base degree-day method, or 3-P change point models
  - Variable base reference temperatures

Data driven

- Simple linear regression
  - One dependent parameter, one independent parameter. May have slope and *y*-intercept
- Multiple linear regression
  - One dependent parameter, multiple independent parameters.
- Change-point models
  - Uses daily or monthly utility billing data and average period temperatures

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Dynamic methods

Forward

- **Simplified dynamic methods**
  - Regresive result analysis from multiple steady-state model run with variable boundary condition
- **Weighting-Factor Method**
  - With this method, space heat gains at constant space temperature are determined from a physical description of the building, ambient weather conditions, and internal load profiles.
- **Response factor**
  - Simple systems dynamic response is possible to describe by diferential equation. Fourier analysis. Frequency domain analysis convertible to time domain time. Analagy with electrical circuits – resitance, capacity, transformer. Thermal and electricity.
- **Heat balance method**
  - Set of equations, describing energy flow paths between nodes (volumes), solved by numerical methods – finite diference method, finite element method

Data-driven

- **Artificial neural networks**
  - Connectionist models.

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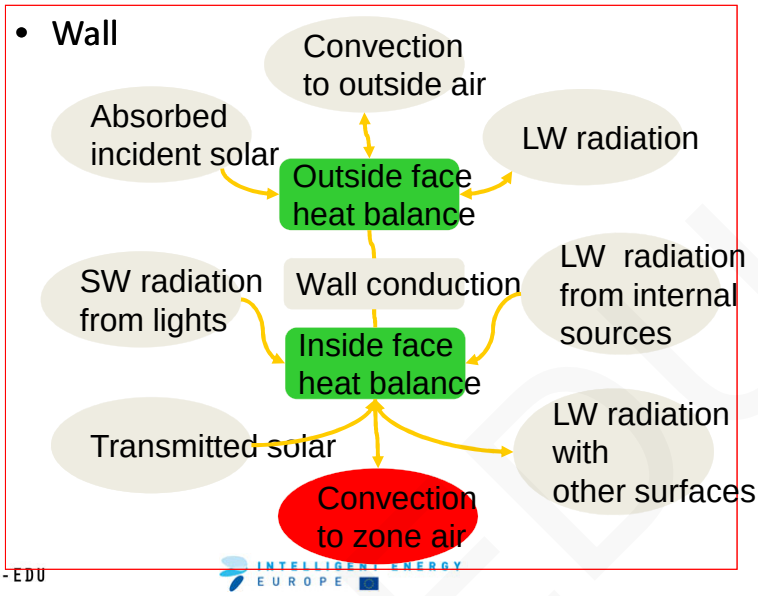
Heat balance method

- Wall



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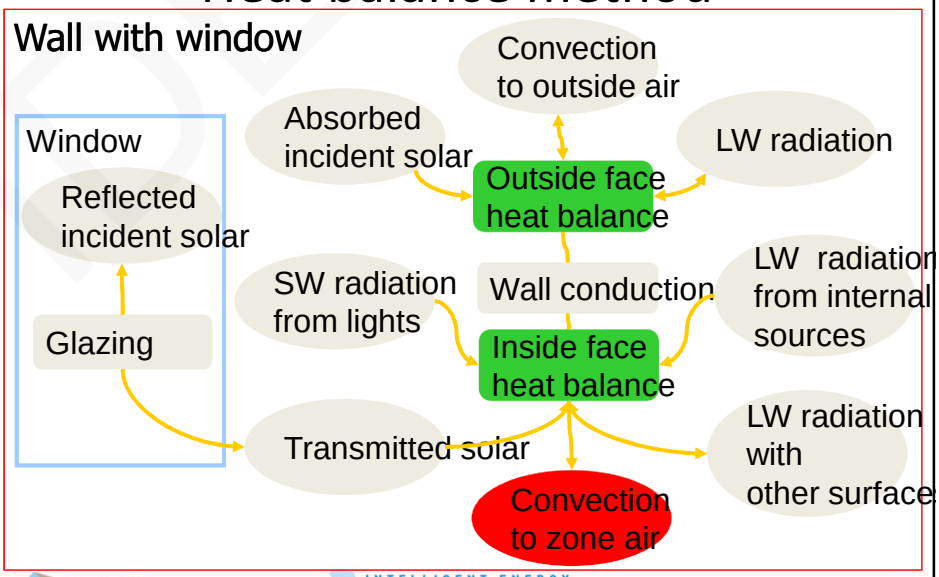
Heat balance method

Wall with window



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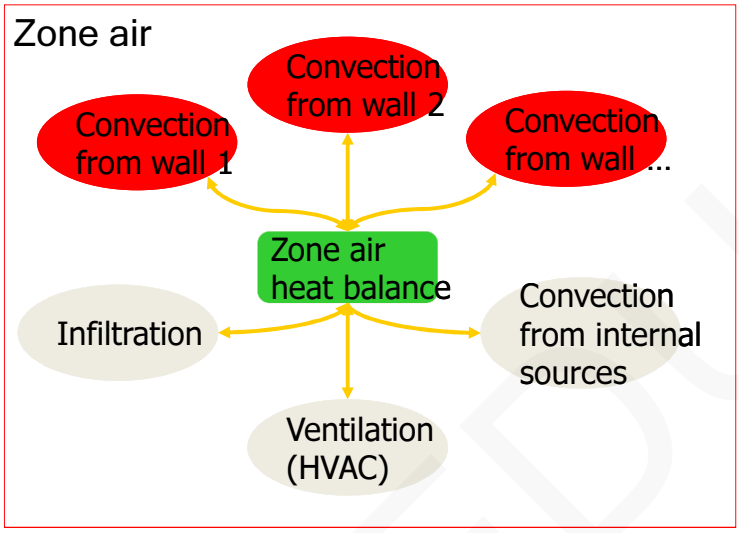
Heat balance method



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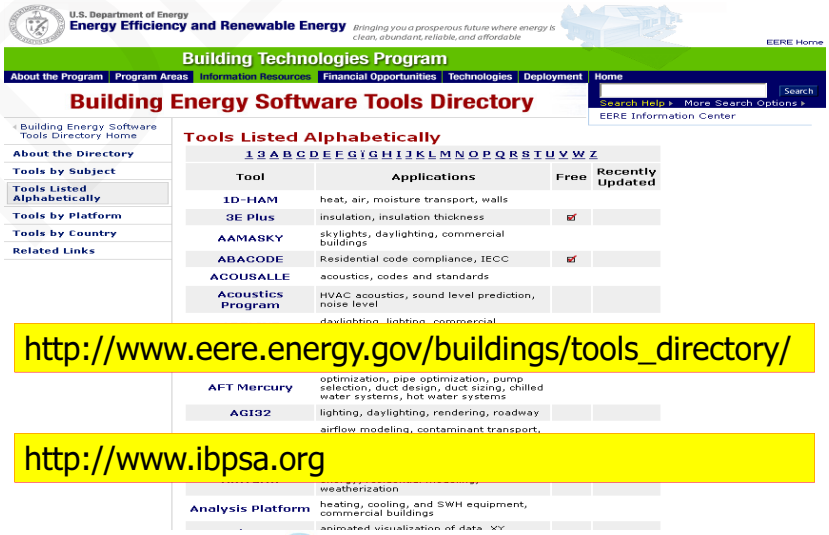
Tools overview



http://www.eere.energy.gov/buildings/tools_directory/

http://www.ibpsa.org

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Building Energy Performance Simulation

ESP-R

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ESP-r background

UNIVERSITY OF STRATHCLYDE

- ESP-r (Environmental Systems Performance; r for "research„)
- Dynamic, whole building simulation finite volume, finite difference sw based on heat balance method.
- Academic, research / non commercial
- Developed at ESRU, Dept.of Mech. Eng. University of Strathclyde, Glasgow, UK by prof. Joseph Clarke and his team since 1974
- ESP-r is released under the terms of the GNU General Public License. It can be used for commercial or non-commercial work subject to the terms of this open source licence agreement.
- UNIX, Cygwin, Windows

http://www.esru.strath.ac.uk/

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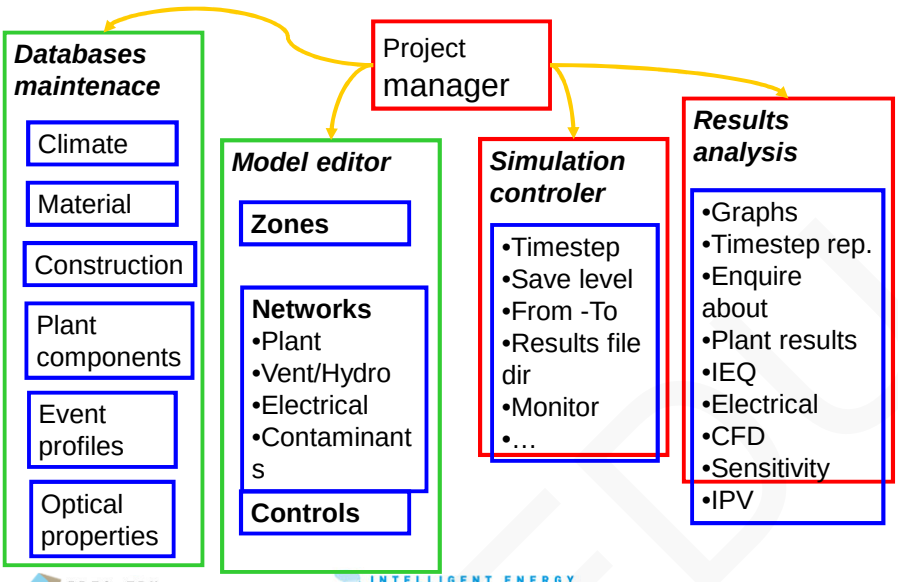
ESP-r architecture



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Case study 1

USE OF ESP-R FOR EVALUATION OF RADIANT HEATING/COOLING SYSTEM WITH CAPILLARY MATS

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PROBLEM DESCRIPTION

- The main purpose of this study was to investigate integrated heating/cooling system performance during typical Central Europe climate conditions with office operation load profile.
  - Is the integrated ceiling heating/cooling system able to secure compliance with comfort requirements during the whole year operation?
  - Are the existing design recommendations in terms of maximum heating/cooling output of the ceiling applicable particularly in climate conditions of Central Europe?

Integrated heating/cooling ceiling system with capillary mats

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PROBLEM ANALYSIS

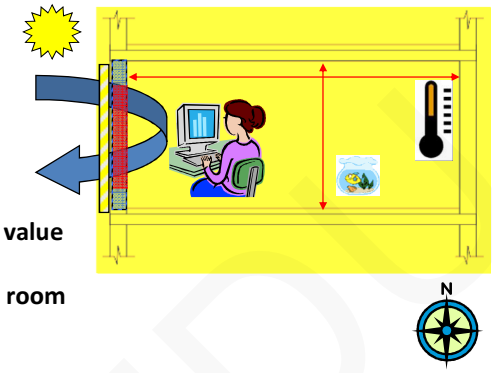
We focused on three types of the buildings, where integrated heating/cooling ceiling system has been used and problems appeared.

- residential building
- office building with small offices
- office building with open space offices

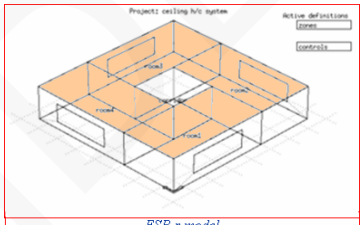
PROBLEM ANALYSIS

At first a list of parameters, that may have any influence on the possibility of the integrated ceiling heating/cooling system application was created.
The list contains following parameters:

- ✓ **Internal sensible heat load**
- ✓ **Internal latent heat load**
- ✓ **Infiltration air rate**
- ✓ **Ventilation air rate**
- ✓ **Humidity control**
- ✓ **Quality of the walls - U value**
- ✓ **Glazing ratio**
- ✓ **Quality of the windows – U,g value**
- ✓ **Active shading – blinds**
- ✓ **Ratio of hight to depth of the room**
- ✓ **Orientation**
- ✓ **Set point for heating**
- ✓ **Set point for cooling**



RESEARCH METHOD

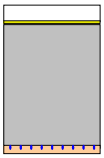


ESP-r model

A five - zone model in ESP-r
Glazing 3o% of one outside wall each zone
Medium-heavy constructions
external wall U = 0.24 W/m^{2}K
internal wall U = 1.56 W/m^{2}K
window U = 1.20 W/m^{2}K, trn=0,76

ESP-r simulation of an annual building energy performance, 1 hour time step

Active Ceiling / Floor construct



System is defined by heating capacity controlled according to established practice in a range of 0-130 W/m^2, cooling capacity 0-80 W/m^2 in each of the rooms. Set point for cooling is 26℃, for heating is 22℃.

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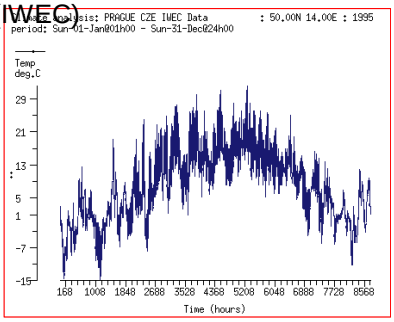
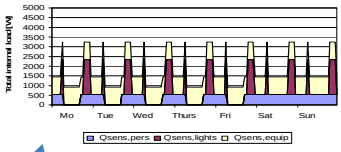
Model operation profiles

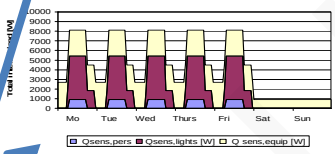
Model was loaded by
- Czech climate conditions (IWEC)



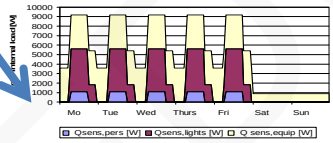
3 alternatives of operation schedules
- occupants (sensible,latent load)
- lights
- equipment



Residential – B1



Small office – K1



Open space office – VK1

SIMULATION RESULTS

CRITERION
- ➢annual heating/cooling energy use
- ➢ comfort expressed by resultant temperatures, PMV and PPD parameters
- ➢ the possibility of condensation on the ceiling surface during the cooling period

Alternative	Heating [kWh/m²/a]	Cooling [kWh/m²/a]
Residential	45.3	69.3
Office	7.4	228.4
Open-space office	7.2	264.9

SIMULATION RESULTS

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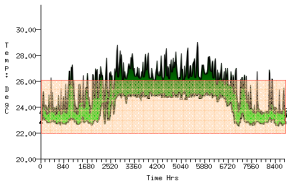
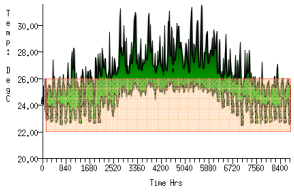
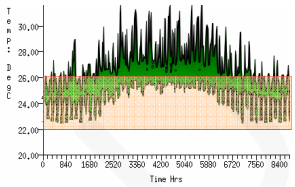


Residential – B1



Small office – K1



Open space office –

? Resultant temperature x db temperature

? Weekends - Peak values

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SIMULATION RESULTS

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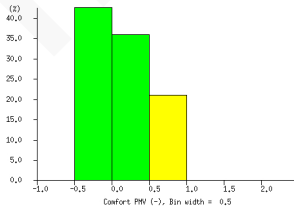
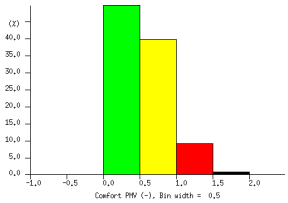
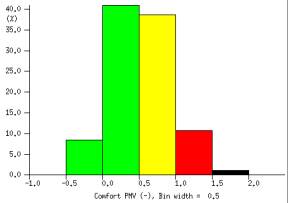


Residential – B1



Small office – K1



Open space office –

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SIMULATION RESULTS

CRITERION

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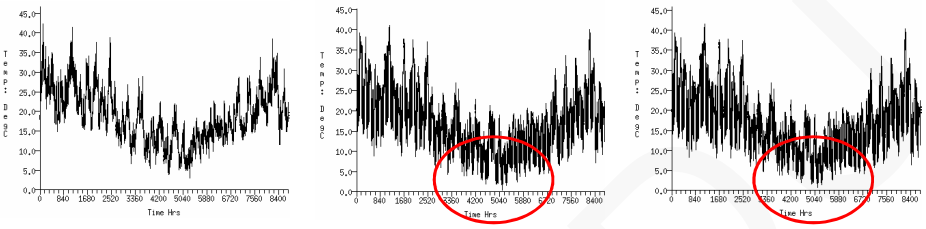

Residential – B1 Small office – K1 Open space office –

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CONCLUSION

- The simulation shows that common design heating/cooling capacities (130 and 80 W/m^2) of the ceiling surface are appropriate for all three simulated cases.
- The system can reliably guarantee the required temperature during the whole year in the heating mode.
- Several problems are detected with the cooling, when the designed capacity cannot cover the temperature requirements and occasionally a short-term condensation can occur.
- The application of this integrated system is limited by its capacity. especially in the buildings with higher internal gains and connected cooling demand this application is disputable.

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Building Energy Performance Simulation Tools

IES,TRNSYS, IDA, ENERGY+

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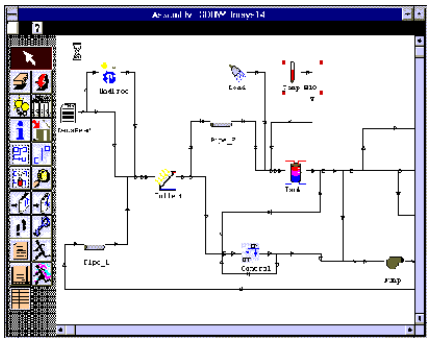
TRNSYS

- Lawrence-Berkeley National Laboratory (USA)
- Simulation buildings and energy systems
- User-friendly interface
- Elements library
- Commercial product



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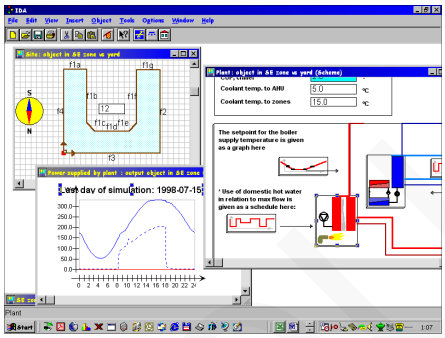
IDA

- Nordic tool (Sweden)
- Modeling and simulation of Buildings and systems
- Databases
- Standard climate data files
- Commercial tool



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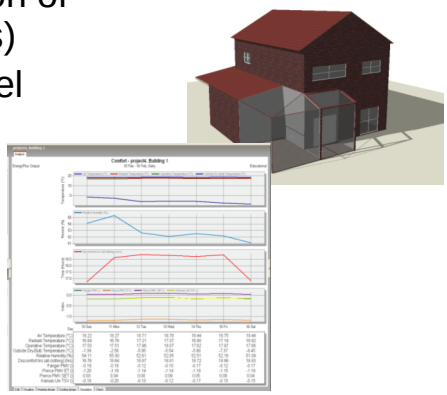
Design Builder (Energy+)

DesignBuilder Software

- US /UK tool
- Modeling and simulation of buildings (and systems)
- Different levels of model detail
- 3D realistic model
- Commercial tool/ free calculation kernel



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IEQ simulation - CFD

FLOVENT,FLUENT…

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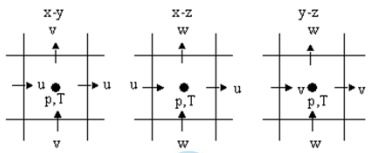
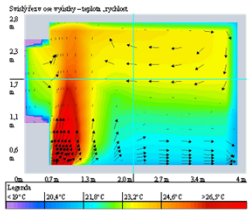
Computational Fluid Dynamics

- Modeling of indoor environment - air flow patterns, temperature distribution, polutantat concentration
  - Aerodynamics of interior or exterior
  - Navier- Stokes equations
  - Temperature, pressure, air flow velocity and direction, radiatin
  - Convergence calculation – turbulent fows, symetry, sensitivity
  - *Tools: Fluent, Flovent,ESP-r…*

$$T = \frac{(C_0T_0 + C_1T_1 + C_2T_2 + C_3T_3 + C_4T_4 + C_5T_5 + C_6T_6 + S)}{(C_0 + C_1 + C_2 + C_3 + C_4 + C_5 + C_6)}$$





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Basic principle of modelling and simulation approach

- Problem analysis – identification of the zones, systems, plant components and their dependencies
- Assignment definition
- Boundary condition definition
- Definition of detail scale and model range
- Proper tool selection
- Sensitivity analysis
- Results validation

„Virtual laboratory is not a design tool, but it can support design process …“

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When to use simulation in building energy performance analysis?

- Early phase of building conceptual design to predict energy performance of the alternative solutions to support designer decision process (building shape, initial facade and shading, HVAC concept)
- Modeling non-standard building elements and systems (double-facade, atrium, natural ventilation, renewables, solar technologies, integrated HVAC systems)
- Investigation of the operational breakdowns and set-up of control systems (HVAC, adaptive control, self-learning systems,…)
- Indoor environment quality prediction (temperatures, air flow patterns, PMV,PPD)
- Analysis of energy saving measures to energy use

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