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Demonstration on District Heating and Cooling

CONSUMER HEATING SYSTEM SIMULATION

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IEA-District Heating and Cooling Project

**CONSUMER HEATING SYSTEM SIMULATION
(CHESS)**

by

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PREFACE AND ACKNOWLEDGEMENTS

The International Energy Agency (IEA) was established in 1974 within the framework of the OECD to implement an International Energy Program. A basic aim of the IEA is to strengthen the cooperation between the member countries in the energy field.

One element of this cooperative activities is to undertake energy research, development and demonstration (RD & D).

District Heating is seen by the IEA as a mean by which countries may reduce their dependence on oil and improve their energy efficiency. It involves increased use of indigenous or abundant fuels, the utilization of waste energy and combined heat- and power production.

IEAs "Program of Research", Development and Demonstration on District Heating" was established at the end of 1983. Under Annex I ten countries did participate in the program: Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, The Netherlands, Norway, Sweden and USA.

The National Energy Administration, Sweden was the Operating Agent for the program under Annex I, in which the following technical areas were assessed:

- * Development of heat meters
- * Cost efficient distribution and connection systems for areas of low heating density
- * Small size coal-fired hot water boiler
- * Medium size combined heat and power plants
- * Low temperature applications in district heating systems

The results of these topics have been presented in printed reports published by the National Energy Administration, Sweden.

In 1987 it was decided by nine of the original ten participating countries (ex. Belgium) to continue the implementation of cooperative projects under an Annex II.

The Netherlands Agency for Energy and the Environment (NOVEM), was Operating Agent for Annex II, in which the following technical areas were assessed:

- * Heat meters
- * Consumer installations
- * Piping
- * Advanced fluids
- * Advanced heat production technology
- * Information exchange

The results of these topics have been presented in printed reports published by NOVEM.

In 1990 the cooperating countries decided to continue the planning and implementation of new cooperative projects under a new Annex III. During this annex United Kingdom joined the project.

NOVEM has been Operating Agent also for Annex III, in which the following technical areas have been assessed:

- * District Heating and the Environment
- * Supervision of District Heating Networks
- * Advanced Fluids
- * Piping
- * District Energy Promotion Manual
- * Consumer Heating System Simulation

This report describe the project called Consumer Heating System Simulation (CHES).

The work on the CHES-project has been monitored by the "IEA-Experts Group on CHES" (EG) with associate professor Rolf Ulseth from the Norwegian Institute of Technology (NTH) as project leader and "Chairman of EG-CHES".

The appointed members of "EG-CHES" have been:

- * Tom Onno (Canada)
- * Benny Böhm (Denmark)
- * Veli-Matti Mäkelä (Finland)
- * H. Bach (Germany)
- * Huub Stroeken (The Netherlands)
- * Rolf Ulseth (Norway)
- * Svend Frederiksen (Sweden)
- * Gary E. Phetteplace (USA)

The Chairman wants to thank everybody who has contributed and made it possible to carry through this work - especially every individual of the EG for making a good effort and showing a positive will to co-operate. A special thank has to be given to Einar M. Hjorthol for his good work on the project. Thanks should also be given to the "Executive Committee" who gave priority to do work on the CHES-project.

On behalf of SINTEF I will also take this opportunity to thank "The Royal Norwegian Council for Scientific and Industrial Research (NTNF)" for the financial support that has made possible the Norwegian participation in "The IEA-District Heating and Cooling Project"

Rolf Ulseth
Chairman of EG-CHES

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SUMMARY

CHES is a PC-based dynamic simulation tool for Consumer Heating Systems especially designed for District Heating.

The tool is also very useful for Heating Systems in general where a great cooling of the hot water is important like in systems with heat pumps.

The CHES-concept is based on a modular structure where the system you want to analyze can be built together from separate models of the actual components in the system.

The basic models take care of the effect of varying water flows and its influence on the heat transfer coefficients.

At this stage of the programme development the linking procedures have to be done by experts. More developing work is needed to enhance the userfriendliness to a level where a non-expert may build his own system configurations.

The programme in hand contains two separate executive program-versions of a chosen "reference system". These executive programmes may be operated very easily by non-experts.

The CHES-concept may be used for several purposes like:

- Optimization of temperature differences and the water cooling in the system
- Evaluating the regulativity of the system
- Choosing the right regulator
- Adjusting the regulator
- Evaluating of regulating valves
- Choosing the right values
- Choosing the right place for the sensors
- Evaluating the regulating consequences of hysteresis etc

The concept makes it possible to evaluate the whole system operation on the design-stage and thereby eliminate bad system configurations at an early stage. The CHES-concept may also be used to analyze existing bad working systems to see the effects of possible changes of the system.

The simulation program is adapted from a simulation tool named CYPROS SIM which is a program for solving nonlinear dynamic problems.

1 INTRODUCTION

The objective is to develop a dynamic simulation tool for consumer heating systems especially designed for district heating. Compared to traditional HVAC systems, those connected to district heating systems differ due to flow control and focus on temperature difference of the primary water. In this report two system concepts are described, one radiator system and one system for ventilation air heating. These two systems are combined as consumer installations and linked to a consumer substation heat exchanger. The total system concept is described in chapter 2.

Some test simulations are presented in chapter 5 to give an idea of the alternative applications of the simulation tools.

A diskette with the executive programmes that are developed may be requested from the member of the "Executive Committee" from your own country or from:

Operating Agent; NOVEM, The Netherlands.

The following reference is recommended:

"IEA-District Heating and Cooling Project", Annex III
"Consumer HEating System Simulation" (CHESS),
November 1992.

2 SIMULATED SYSTEM CONCEPTS

The simulated system concept contains one radiator system and one for ventilation air heating. The two subsystems are coupled in parallel and linked to a consumer substation heat exchanger. There are usually two alternative system solutions used when connecting radiator and ventilation air heating systems to district heating. Alternative 1 is shown in Figure 2.1 where 2-port valves are used for temperature control. Alternative 2 is shown in Figure 2.2 where 3-port valves are used for temperature control.

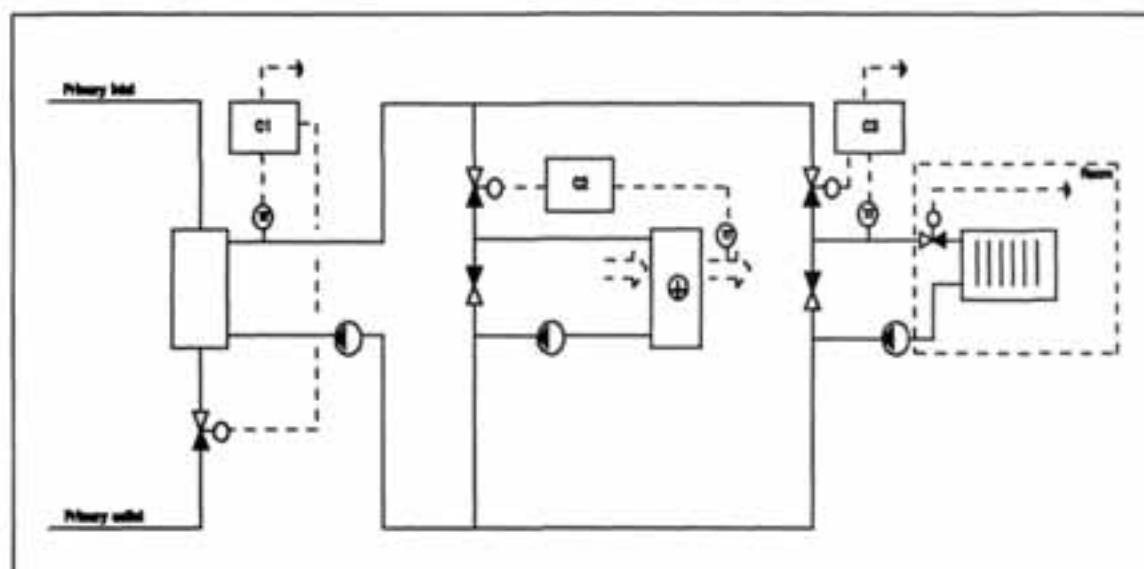


Figure 2.1 Total system concept with (from the left) consumer substation heat exchanger, ventilation air heating system and radiator system.

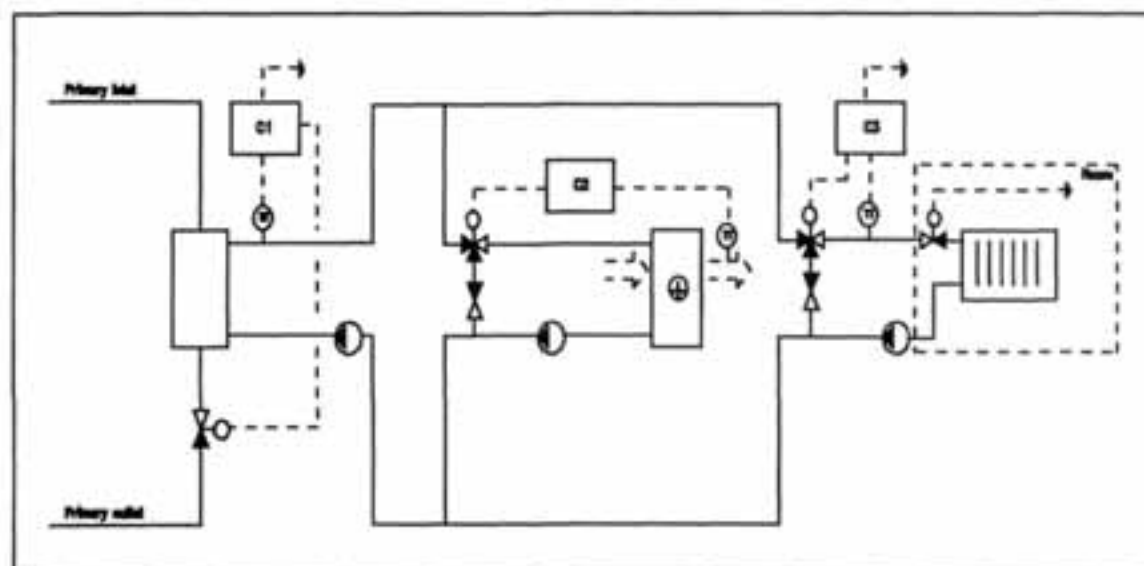


Figure 2.2 Consumer subsystems with 3-port valve for temperature control

3 SIMULATION PROGRAM DESCRIPTION

The simulation program is adapted from a simulation tool named CYPROS SIM, which is a program for solving nonlinear dynamic problems. The SIM program is mainly a shell containing various numerical solutions for solving differential equations. The program is also supported by flexible input/output routines for data presentation.

The adaption of the program primarily consists of developing a modular system solution. A modular structure is essential to enable a smooth and flexible change of system solutions, and each component is described by its own subroutine. The modular simulation technique greatly reduces the complexity of system simulation because it essentially reduces a large problem into a number of smaller problems, each of which can be more easily solved independently. In addition many components are common to different systems as well as being repeated within one system. Provided the performance of these components is described in a general form, they can be used in many different systems and many times within the same system with little or no modification.

The simulation tool contains two separate executive programs, one for consumer systems with 2-port valves, **CHESS2V**, and one for consumer systems with 3-port valves, **CHESS3V**.

3.1 Manual for operating "CHESS"

The manual will give a brief description of:

- o Requested hardware
- o Installation
- o The user interface
- o Special features on system simulation
- o Parameter description
- o Error messages

3.1.1 Requested hardware

- o An IBM PC/XT, AT, 386, 486 or compatible. 386 or 486 is recommended.
- o MS-DOS version 2.10 or higher.
- o Minimum 512 kb memory, 640 kb is recommended.
- o Floating Point Coprocessor (Intel 80287, 80387 or 80487)
- o Graphics capability.

3.1.2 Installation

The complete content of the floppy must be copied to your PC on the same directory. You are free to create any suitable directory for the simulation tool.

In order to run the graphic result presentation you must choose a proper graphic driver. A list

of proper graphic drivers is found on the next page.

1. Find the identification number, n, of your configuration from the table on the next page
2. Place the following in your AUTOEXEC.BAT SET CYPROSDISP = n
E.g. EGA 640*350 16 color: n = 560

The most frequently used graphics drivers:

3.1.3 The user interface

A complete simulation example is revealed in appendix A1.

The simulation program is started by typing: **CHESS2V <CR>** or **CHESS3V <CR>**, depending on simulating system with 2-port valves or 3-port valves.

The program now asks for the datafile which has corresponding names, CHESS2V or CHESS3V.

The following text will now appear on the screen: **Main Command set (simulation):.....**

By typing **xyz** the available options will be listed:

Data-file:	Operations on the data-file, change parameters and initial values etc.
Simulation:	Choose solution method, specify time interval, stepsize etc and simulate.
Output:	Show the results on screen, as numeric tables or on TS-files.
Parameter:	Change system parameters, eg. the dimension of the solution table.
Call-User:	Execute subroutine USER once
Help:	Not included
Exit:	Leave the program.

By typing the first letter in the available options and <CR> the command will be executed.

Figure 3.1 shows the simulation tool communication structure.

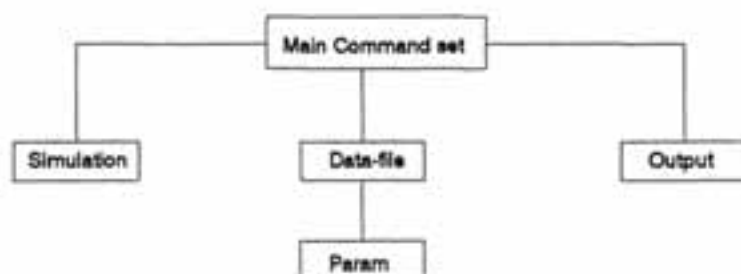


Figure 3.1 Simulation tool communication structure

Before you continue the reading you should notice the content of point 3.1.4.

Running "Simulation" mode:

In this mode your simulation problem will be solved. You will here interactively choose which method to use (Euler) and decide time interval and step size. The simulation tool also provide alternative solution methods to Euler which will not be described in this text.

Note that you can halt a run by pressing any key during simulation. If you want to restart the simulation you enter the "Parameter" option and turns SUSPEND ON (no. 4).

When running "Simulation" mode the following text will occur:

Solution method (Euler):.....	: Euler	Euler is the default value which should be used
Time interval (Ti,Tf) (0.0,0.0)....	: 0,10	Initial simulation to create parameterstructure
Step size(0.0).....	: 0.1	"Normal" step size for this system
Simulating.....		If you just want to run the system with default parameters you should set Tf > 400
=====>		
# of samples	100	
# stored	100	
Main command set (output)....	:	When the simulations are completed the system returns to the "Main command set"

After this initial simulation sequence it is possible to change parameters of the various system components by entering "Data-file" mode.

Running "Data-file" mode

In this mode you can change the initial parameter values of the system components. You can

also write to new data files, or read from old files. You can also specify the variables you want to store during a simulation. A predecided set of parameters are normally stored.

Typing **xyz** the available options will be listed:

Change:	not in use
Nostore:	With this command you can specify the variables which you wish not to be stored during simulation
Store:	With this command you can make the variables restored again
Read:	Read from specified *.DAT file
Write:	Write to specified *.Dat file
Update:	Updates the initial process and control states with the actual states
Param:	Enables change of initial parameters
Oppdat:	Updates the parameter states, eg. flow variables.
0-Exit:	Return to "Main Command" level

The three most used facilities are Update, Oppdat and Param. Typing "Param" the following will be listed:

MODEL NO	1 IS	EXCITATION 1
MODEL NO	2 IS	HEAT EXCHANGER 1
MODEL NO	3 IS	CONTROL VALVE 1
MODEL NO	4 IS	CONTROLLER 1
MODEL NO	5 IS	PIPE 1
MODEL NO	6 IS	PIPE 2
MODEL NO	7 IS	PIPE 3
MODEL NO	8 IS	PIPE 4
MODEL NO	9 IS	CONTROL VALVE 2
MODEL NO	10 IS	CONTROLLER 2
MODEL NO	11 IS	EXCITATION 2
MODEL NO	12 IS	PIPE 5
MODEL NO	13 IS	HEAT EXCHANGER 2
MODEL NO	14 IS	PIPE 6
MODEL NO	15 IS	VENTILATION DUCT
MODEL NO	16 IS	CONTROL VALVE 3
MODEL NO	17 IS	CONTROLLER 3
MODEL NO	18 IS	PIPE 7
MODEL NO	19 IS	RADIATOR 1
MODEL NO	20 IS	PIPE 8
MODEL NO	21 IS	CONTROL VALVE 4
MODEL NO	22 IS	CONTROLLER 4
NO	23 IS	GLOBAL VARIABLES

WRITE MODNO: (0).....:

By typing the model number and <cr> the model parameters will appear on the screen and can be adjusted by typing the new value and using the space bar. The "Global Variables" contains volume flows and controller output signals besides thermodynamic properties.

Typing 0 and <cr> twice brings you back to "Main command set" and a simulation with the new parameters may be performed.

Running "Output" mode:

When the simulation is completed, you can enter "Output" mode. Here you select how to present the results. By typing xyz the following options will appear:

Show-Result:	Display the result on screen
Keep-Result:	Copy all variables from the solution table to a specified TS-file
List-Result:	Show the result as numeric tables on terminal, printer or ASCII-file. Up to 3 variables separated by commas can be shown simultaneously
Append-Result:	Append the result to an existing TS-file.
0-Exit:	Return to Main Command level

By using List-Result and ASCII-file the data can be prepared and presented by using eg. Lotus 123.

3.1.4 Special features on system simulation

System evaluation request an initial stable system before starting the simulation sequence. The following instructions will indicate how to stabilize the system and how to perform simulations:

1. If you want to change model parameters you have to do an initial short simulation to establish the parameter structure.
2. Enter the "Data-File" mode and choose the option PARAM.
3. Change the requested model parameters
4. Enter "Simulation" mode and do a long simulation (2-3000 sec.) to stabilize the system.
5. Check if the system is stable by controlling strategic temperature states in "Output" mode (show-result). See figure 3.2.
6. When unstable system, enter "Data-File" mode and use the options UPDATE and OPPDAT and repeat from point 4.
7. When stable system, enter "Data-File" mode and use the options UPDATE and OPPDAT and PARAM.
8. Now the system can be exposed to variation in eg. inlet temperatures, volume flows, controller setpoints etc.

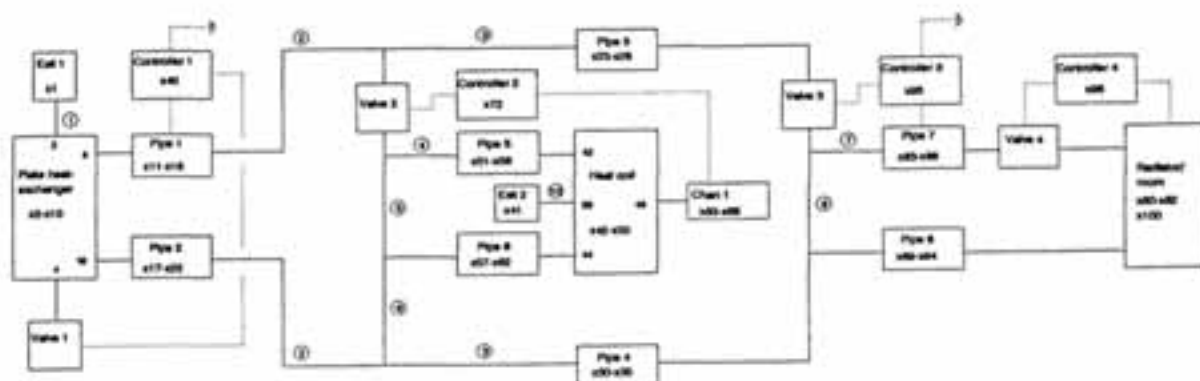


Figure 3.2 System configuration

The different x-values in the models describe the states that appear in the model. A closer description is found in 3.1.5 Parameter description. The flow-states are described by numbers in circles. These flow-states are found in "Global Parameters", no 23.

3.1.5 Parameter description

The parameter description will describe the parameters input coupled to the various models.

Excitation models.

There exist two excitation models, one where the temperature can be altered and one where both the temperature and the flow can be altered:

Excitation alternative 1

Inlet temperature [°C]
Alteration time
New inlet temperature

Excitation alternative 2

Inlet temperature [°C]
Alteration time
New inlet temperature
Realteration time
Initial flow [m³/s]
New flow [m³/s]

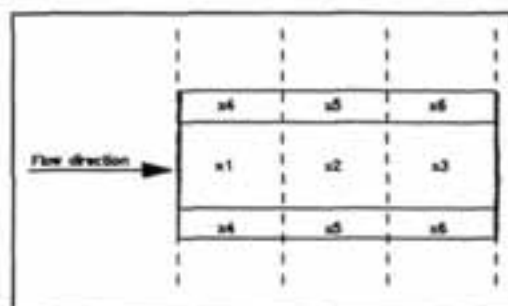
The excitation model is described by one state. The flow parameter is found under Global Parameters no. 23.

Pipe model.

The pipe model is described by 5 parameters:

Pipe length [m]
Inside diameter [m]
Outside diameter [m]
Wall heat capacity [J/kg°C]
Density pipe [kg/m³]

The pipe model is described by 6 states. The first 3 describes the flow temperatures and the last 3 describes the wall.

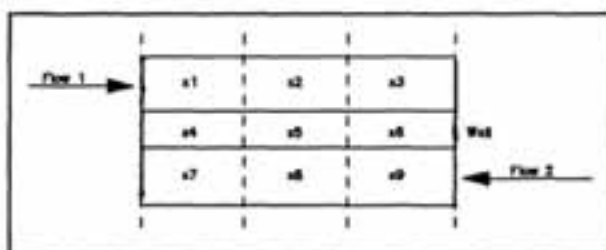


Heat exchanger.

The heat exchanger model is a plate heat exchanger described by 8 parameters, but the parameter list contains 12 parameters where 4 are so called not changeable:

- Wall thickness [m]
- Distance between plates [m]
- Width plates [m]
- Height plates [m]
- Shape factor
- Number of plates
- Density plates [kg/m³]
- Heat capacity plates [J/kg°C]

The shape factor is used to adjust for static deviation between measured and simulated states. The heat exchanger is described by 9 states where the first and last three are flow temperatures.

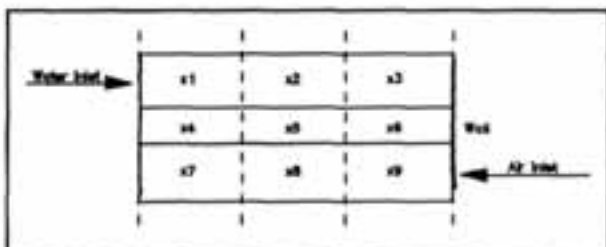


Heat coil.

The heat coil model is described by 9 parameters:

- Heat coil mass [kg]
- Water volume [m³]
- Design value air flow [m³/s]
- Design value air in [°C]
- Design value air out [°C]
- Design value water in [°C]
- Design value water flow [m³/s]
- Nominal heat transfer coefficient water [W/m²°C]
- Nominal heat transfer coefficient air [W/m²°C]

The default values describe a heat coil with load capacity of 20 kW. The heat coil is described by 9 states where the first and last three are flow temperatures.



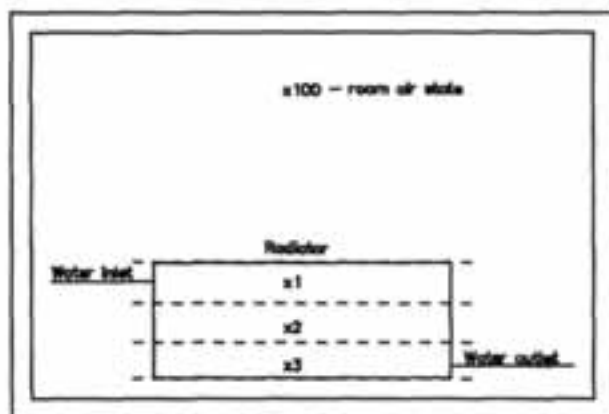
Radiator

The radiator model is described by 6 parameters. In addition the load demand and the room heat capacity are described in the same model:

- Radiator surface area [m²]
- Water volume in radiator [m³]
- Radiator weight [kg]
- Radiator emissivity

Radiator heat capacity [J/kg°C]
 Radiator height [m]
 Load demand [W]
 Room heat capacity [J/°C]

The radiator is described by 3 states. In addition the room temperature is named x100.



Control valves

In the subsystems a 2-port valve is used, but these subsystems can also in principle use a 3-port valve. In this text the parameter description of both 2-port and 3-port valve is described:

2-port valve

Kvs control valve [m³/h]
 Valve authority
 Valve characteristic [0-lin.,1-quad.,2-exp.]
 Pressure difference [bar]
 Control ratio
 Actuator speed [s]
 Hysteresis [0-1]
 Actuator position
 Valve position
 Previous actuator position
 Delta V

3-port valve

Kvs control port [m³/h]
 Valve authority control port
 Characteristic control port [0-lin.,1-quad.,2-exp.]
 Kvs shunt port [m³/h]
 Valve authority shunt port
 Characteristic control port [0-lin.,1-quad.,2-exp.]
 Actuator speed [s]
 Hysteresis [0-1]
 Actuator position
 Valve position
 Previous actuator position
 Delta V
 Range
 Pressure difference control port [bar]
 Pressure difference shunt port [bar]

Parameters from "Actuator position" to "Delta V" are addressed automatically and should not be changed.

Controller.

The controller is described by 8 parameters:

Sensor time constant [s]
 Sensor time delay [s]
 Controller gain [1/°C]
 Controller integration time [s]
 Controller derivation time [s]
 Controller reference temperature
 Previous control error [°C]
 Sum integration element

The one state described in the controller is the sensor temperature. "Previous control error" and "Sum integration element" are addressed automatically and should not be changed.

3.1.6 Error messages

The model parameters used as default values secure a correct simulation with a time step of 0.1 seconds. Unfortunate choice of model parameters can lead to error during simulations which usually occur as rolling error messages on the screen. The reason for the error is usually high flow speed in a part of the system. The following procedure should be used when error messages occur:

1. Press <CR> to stop the simulation
2. Write **P** <CR> to enter "system parameter" option
3. Write **4** <CR> to turn suspend off which enables a restart of the simulation
4. There are two alternatives when restarting the simulations:
 - a. reduce the time step
 - b. change critical parameters eg. flow capacities and pipe dimensions
5. A third possibility is to do a complete restart of the program which will start with default values.

Note that an increase in pipe length and pipe diameter will reduce the risk of errors appearing during simulations.

4 MODEL DESCRIPTION

The model description contains mathematical description of all the models used in the simulation tool.

The models described in detail are:

- o Heat coil
- o 3-port valve
- o Radiator

The following models are also used in the simulation tool and are described in detail in Hjorthol /1/:

- o Temperature sensor
- o Plate heat exchanger
- o Tube
- o Controller
- o Actuator
- o 2-port valve

The listed models will be subject to a short description in section 4.4.

4.1 Heat coil

There are two major problems which must be considered when modelling the heat coil:

1. The input values must be easy to specify
2. The mathematical description must not be too complex.

On this basis the input values were chosen to be:

- o Heat coil mass
- o Heat coil water volume
- o Design air flow
- o Design air inlet temperature
- o Design air outlet temperature
- o Design water inlet temperature
- o Design water flow

The mass flow dependence of the heat transfer coefficient are obtained by using a nominal heat transfer coefficient at design flows. The outside and inside heat transfer coefficients are calculated on the basis of the design coefficients and the volume flow.

The heat coil is modelled using water, wall and air as separate elements, see figure 4.1. The mathematical description is based on general energy equations:

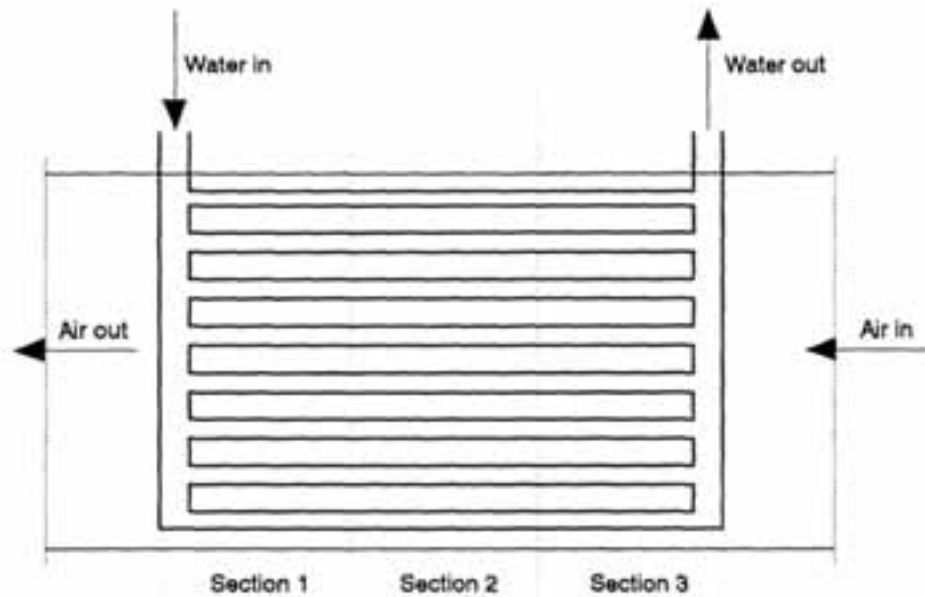


Figure 4.1 Heat coil model

Tube liquid:

$$\frac{\delta}{\delta t}(\rho_w \cdot V_{wn} + c_{pw} \cdot T_{wn}) = \rho_w \cdot \dot{V}_w + c_{pw}(T_{w(n-1)} - T_{wn}) - h_1 \cdot A_{in}(T_{wn} - T_{in})$$

$$\frac{\delta}{\delta t} T_{wn} = \frac{\dot{V}_w \cdot N}{V_w} (T_{w(n-1)} - T_{wn}) - \frac{h_1 \cdot A_i}{\rho_w \cdot V_w + c_{pw}} (T_{wn} - T_{in})$$

Shell wall:

$$\frac{\delta}{\delta t}(\rho_t \cdot V_{tn} + c_{pt} \cdot T_{tn}) = h_1 \cdot A_{in}(T_{wn} - T_{tn}) - h_2 \cdot A_{on}(T_{tn} - T_{an})$$

$$\frac{\delta}{\delta t} T_{tn} = \frac{h_1 \cdot A_i}{\rho_t \cdot V_t + c_{pt}} (T_{wn} - T_{tn}) - \frac{h_2 \cdot A_o}{\rho_t \cdot V_t + c_{pt}} (T_{tn} - T_{an})$$

Air:

$$\frac{\delta}{\delta t}(\rho_a * V_{an} * c_{pa} * T_{an}) = \rho_a * \dot{V}_a * c_{pa} (T_{a(n+1)} - T_{an}) - h_2 * A_{on} (T_{in} - T_{an})$$

$$\frac{\delta}{\delta t} T_{an} = \frac{\dot{V}_a * N}{V_a} (T_{a(n+1)} - T_{an}) - \frac{h_2 * A_o}{\rho_a * V_a * c_{pa}} (T_{in} - T_{an})$$

Nomenclature:

ρ_w	-	density water
V_{wn}	-	volume water section n
c_{pw}	-	specific heat capacity water
T_{wn}	-	temperature water section n
h_1	-	convective heat transfer coefficient inside tubes
h_2	-	convective heat transfer coefficient outside tubes
A_{in}	-	inside tube area section n
A_{on}	-	outside tube area section n
N	-	number of sections
ρ_s	-	density heat coil
V_{sn}	-	volume heat coil section n
c_{ps}	-	specific heat capacity heat coil
T_{sn}	-	temperature heat coil section n
ρ_a	-	density air
V_{an}	-	volume air section n
c_{pa}	-	specific heat capacity air
T_{an}	-	temperature air section n

Number of tubes:

Number of tubes is used mainly to calculate the inside and outside heat transfer coefficients on the basis of an approximated tube length, L_r and an assumed inside tube diameter, d_i . Both values can be made dependent of number of tube rows and heat coil load. The preliminary values used are:

Assumed tube length:	L_r	=	0.5 m
Assumed inside diameter:	d_i	=	0.015 m

$$\text{Number of tubes: } n = \frac{V_w * 4}{\pi * L_r * d_i^2}$$

Inside area tubes:

Inside area tubes are also calculated on the basis of an approximated tube length, L_r and an assumed inside tube diameter, d_i . Both values can be made dependent of number of tube rows and heat coil load.

$$\text{Inside area tubes: } A_i = \pi * d_i * L_r * n$$

Outside area heat coil:

The outside area is calculated on the basis of inside area and a shape factor M. By studying various heat coils the factor M is found to be 10 - 20. In this preliminary study the value is set to be 15.

$$\text{Outside area heat coil: } A_o = A_i * M$$

Volume of tubes and lamellas:

The volume of tubes and lamellas is based on the total heat coil mass, m_t , and an average density, ρ_t .

$$\text{Volume of tubes/lamellas: } V_t = \frac{m_t}{\rho_t}$$

Air volume:

The air volume inside the heat coil is calculated to be 3 - 5 times as high as the volume of tubes and lamellas. In this preliminary study the factor K is set to be 4.

$$V_a = V_t * 4$$

Inside and outside convective heat transfer coefficient:

The inside and outside convective heat transfer coefficient is based on the nominal heat transfer coefficient and varies as a function of volume flow. The exponent in the equation calculating the heat transfer coefficients is dependent on the flow regime. The flow area inside the tubes is so big that the flow in most cases is laminar, while the air flow in most cases is turbulent.

$$\text{Inside convective heat transfer coefficient: } h_1 = h_{1nom} * \left(\frac{\dot{V}_w}{\dot{V}_{wnom}} \right)^{0.33}$$

$$\text{Outside convective heat transfer coefficient: } h_2 = h_{2nom} * \left(\frac{\dot{V}_a}{\dot{V}_{anom}} \right)^{0.8}$$

Static model evaluation

A complete static and dynamic model verification is beyond the limits of this project. We have made a static evaluation of the model based on variation in water and air volume flow which gives a view of various operating situations.

The water and air flow was varied in three levels. The deviation between catalogue data and simulations was less than 6 %.

4.2 3-port valve /1/

The 3-port valve is modelled as two separate valves where the valve authority, the valve characteristic, valve size and driving pressure difference can be given separate for the two valves. The valve model also includes a hysteresis routine. The control port and shunt port position are interlocked, and the control port position is described by the value z , which varies between 0 and 1. The shunt port position is described as $1-z$. The volume flow through the control port and shunt port is modelled as follows /1/:

$$\text{Volume flow: } F = \sqrt{\frac{(k_{vs} * f(z))^2 * \Delta p * \frac{\rho_0}{\rho_1}}{1 + (k_{vs} * f(z))^2 * \Delta p * (1-a) * \left(\frac{1}{F_{max}^2} \right) * \frac{\rho_0}{\rho_1}}}$$

Linear valve

$$\text{control port: } f(z) = \left(1 - \frac{1}{R}\right) * z + \frac{1}{R}$$

$$\text{shunt port: } f(z) = \left(1 - \frac{1}{R}\right) * (1-z) + \frac{1}{R}$$

Quadratic valve

$$\text{control port: } f(z) = \left(1 - \frac{1}{R}\right) * z^2 + \frac{1}{R}$$

$$\text{shunt port: } f(z) = \left(1 - \frac{1}{R}\right) * (1-z^2) + \frac{1}{R}$$

Exponential valve

$$\text{control port: } f(z) = R^{z-1}$$

$$\text{shunt port: } f(z) = R^{-z}$$

Nomenclature:

F	-	volume flow
F_{max}	-	nominal volume flow
k_{vs}	-	volume flow through fully open valve at 20°C and 1 bar pressure difference $f(z)$ - valve characteristic
Δp	-	pressure difference of total system
ρ_0	-	density of water at 20°C
ρ_1	-	density of water at actual temperature
a	-	valve authority
R	-	control ratio
z	-	valve position

4.3 Radiator and room model /2/

The radiator model may be used in combination with a room model in addition to thermostatic valve and a conventional heating system, see figure 4.2.

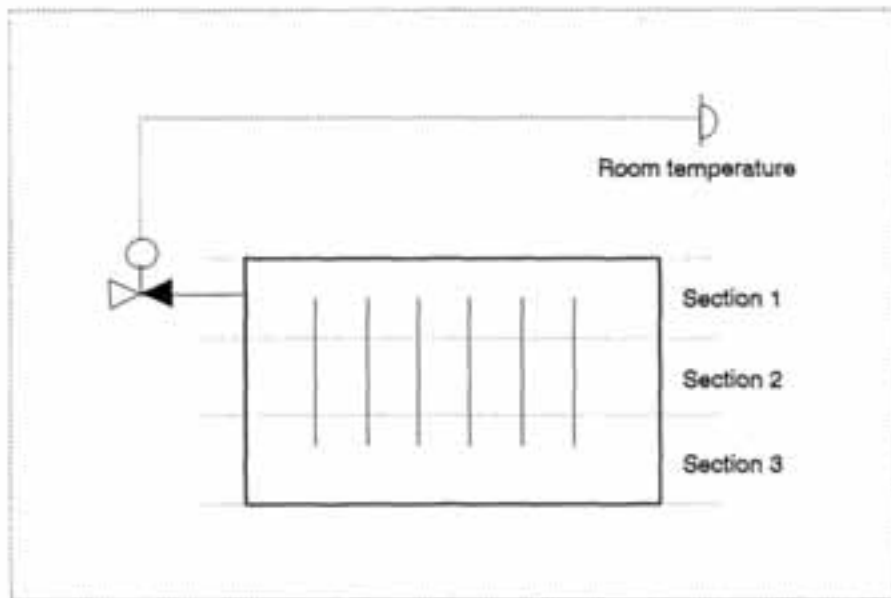


Figure 4.2 Radiator and room model

Heat flow from radiator to room:

$$P_r = P_{str} + P_{conv}$$

$$P_{str} = e \cdot \sigma \cdot A_{rs} (T_{rs}^4 - T_{room}^4)$$

$$P_{conv} = h \cdot A_{rad} \cdot (T_{rs} - T_{room})$$

Heat transfer coefficient:

$$Nu = C \cdot Gr^{\alpha} \cdot Pr^{\beta} = \frac{h \cdot l}{\lambda}$$

For conventional temperature levels the air flow pattern is laminar /1/, and the coefficients

are: $C = 0.59$, $n = m = 0.25$ /2/

The radiator surface temperature can be approximated as follows /3/:

$$T_{rs} = \frac{T_{room} + 4 * T_{wn}}{5}$$

Radiator model:

$$\frac{\delta}{\delta t} * T_{wn} = \frac{F * C_{pw} * (T_{w(n-1)} - T_{wn}) - P_{str} - P_{conv}}{m_{wn} * C_{pw} + m_{radn} * C_{prad}}$$

Room model:

$$\frac{\delta}{\delta t} * T_{room} = \frac{P_r - P_{loss}}{M_{room}}$$

$$P_{loss} = P_{lossnom} \left(\frac{T_{room} - T_{mod}}{T_{ref} - T_{mod}} \right)$$

Nomenclature:

P_r	-	heat load from radiator to room
P_{str}	-	radiation load from radiator to room
P_{conv}	-	convection load from radiator to room air
ϵ	-	emissivity
σ	-	Stefan-Boltzmann constant
A_{rs}	-	surface area radiator
A_{rad}	-	total radiator area
T_{rs}	-	radiator surface temperature
T_{room}	-	room temperature
T_{wn}	-	water temperature element n
h	-	convective radiator heat transfer coefficient
l	-	characteristic length (radiator height)
λ	-	thermal conductivity
F	-	mass flow water
m_{wn}	-	mass water element n
m_{radn}	-	mass radiator element n
C_{pw}	-	specific heat capacity water
C_{prad}	-	specific heat capacity radiator
M_{room}	-	heat capacity room, room air and walls
$P_{lossnom}$	-	nominal heat loss at minimum outdoor design temperature
T_{mod}	-	minimum outdoor design temperature
T_{ref}	-	room reference temperature

Static model evaluation

A complete static and dynamic model verification is beyond the limits of this project. We have made a static evaluation of the model based on variation in load demand and inlet water temperature in four levels. Simulations are compared to measurements presented in Pedersen /4/.

The deviation between measurement data and simulations was less than 8 %.

4.4 Description of models verified in Hjorthol /1/

As noted earlier in this chapter the following models are already verified in Hjorthol /1/ and are therefore subject only to a short description:

- o Temperature sensor
- o Plate heat exchanger
- o Tube
- o Controller
- o Actuator
- o 2-port valve

4.4.1 Temperature sensor

The temperature sensor is modelled using the sensor time constant as a describing parameter. This model is based on the following assumptions:

- o uniform temperature in the sensor*
- o the convection is constant*

The sensor model is incorporated in the controller subroutine.

Mathematical description

$$\frac{\delta}{\delta t}(\rho_s \cdot c_{ps} \cdot V_s \cdot T_s) = U \cdot A_s \cdot (T_w - T_s)$$

$$U = \frac{1}{\frac{1}{h} + \frac{D}{2 \cdot \lambda}}$$

$$\frac{\delta}{\delta t}(\rho_s \cdot c_{ps} \cdot \frac{\pi \cdot D^2 \cdot L}{4} \cdot T_s) = U \cdot \pi \cdot D \cdot L \cdot (T_w - T_s)$$

$$\frac{\delta}{\delta t} T_s = \frac{U \cdot 4}{\rho_s \cdot c_{ps} \cdot D} \cdot (T_w - T_s)$$

$$\frac{\rho_s \cdot c_{ps} \cdot D}{U \cdot 4} = \text{sensor time constant}$$

Nomenclature

T_s	-	sensor temperature
T_w	-	water temperature
c_{ps}	-	sensor specific heat capacity
ρ_s	-	sensor density
V_s	-	sensor volume
A_s	-	sensor outside area
U	-	overall heat transfer coefficient
L	-	sensor length
D	-	sensor diameter

4.4.2 Plate heat exchanger

The model is based on general thermodynamics and previous work done by Gummerus /3/ and the following assumptions.

- o uniform temperature in each element*
- o no conduction in the water flow direction*
- o no conduction in the length direction of the plates*
- o negligible temperature gradient in the walls*
- o no heat loss to the surroundings*
- o fouling is not touched*

Mathematical description

Cold water:

$$\frac{\delta}{\delta t} T_{1wn} = \frac{F_1 \cdot 2 \cdot N_s}{H_p \cdot B_p \cdot \delta_p \cdot N_p} (T_{1w(n-1)} - T_{1wn}) - \frac{h_1 \cdot 2 \cdot (N_p - 1) \cdot S}{\rho_{1w} \cdot c_{p1w} \cdot N_p \cdot \delta_p} (T_{1wn} - T_m)$$

Hot water:

$$\frac{\delta}{\delta t} T_{2wn} = \frac{F_2 \cdot 2 \cdot N_s}{H_p \cdot B_p \cdot \delta_p \cdot N_p} (T_{2w(n-1)} - T_{2wn}) - \frac{h_2 \cdot 2 \cdot (N_p - 1) \cdot S}{\rho_{2w} \cdot c_{p2w} \cdot N_p \cdot \delta_p} (T_{2wn} - T_m)$$

Wall:

$$\frac{\delta}{\delta t} T_m = h_1 \cdot \frac{(N_p - 1) \cdot F}{\rho_t \cdot c_{pt} \cdot \delta_t \cdot N_p} (T_{1wn} - T_m) - h_2 \cdot \frac{(N_p - 1) \cdot F}{\rho_t \cdot c_{pt} \cdot \delta_t \cdot N_p} (T_m - T_{2wn})$$

Nomenclature:

T_{1wn}	-	cold water temperature in section n
T_{2wn}	-	hot water temperature in section n
T_m	-	wall temperature in section n
c_{p1w}	-	cold water specific heat capacity
c_{p2w}	-	hot water specific heat capacity
c_{pt}	-	wall specific heat capacity
ρ_{1w}	-	cold water density
ρ_{2w}	-	hot water density
ρ_t	-	wall density
V_{1wn}	-	cold water volume in section n
V_{2wn}	-	hot water volume in section n
V_m	-	wall volume in section n
F_1	-	cold water volume flow
F_2	-	hot water volume flow
A_{1n}	-	heat transfer area cold side in section n
A_{2n}	-	heat transfer area hot side in section n
A_s	-	flow area
h_1	-	cold side heat transfer coefficient
h_2	-	hot side heat transfer coefficient
H_p	-	heat exchanger height
B_p	-	heat exchanger width
δ_p	-	distance between plates
δ_t	-	plate thickness
S	-	shape factor plates
N_p	-	number of plates
N_s	-	number of sections

4.4.3 Tube

The tube element is used as a linkage between other components included in the system solutions. This model deals with the thermal behaviour of fluid flowing in tubes. The most interesting quantities related to the model are flow rate and temperature. The following assumptions are made:

- o* uniform temperature in each element
- o* no conduction in the water flow direction
- o* no conduction in the wall material
- o* the pipe is ideally insulated

Mathematical description:

Tube liquid:

$$\frac{\delta}{\delta t} T_{wn} = \frac{F \cdot N_s}{\pi \cdot D_i^2 \cdot L} (T_{w(n-1)} - T_{wn}) - \frac{h \cdot A}{\rho_w \cdot c_{pw} \cdot D_i} (T_{wn} - T_{in})$$

Tube wall:

$$\frac{\delta}{\delta t} T_{wn} = \frac{h \cdot A \cdot D_i}{(D_i - D_o)^2 \cdot \rho_t \cdot c_{pt}} (T_{wn} - T_{in})$$

Nomenclature:

T_{wn}	-	water temperature in section n
T_{in}	-	tube temperature in section n
c_{pw}	-	water specific heat
c_{pt}	-	tube specific heat
ρ_w	-	water density
ρ_t	-	tube density
F	-	volume flow through tube
h	-	tube inside heat transfer coefficient
D_i	-	tube inside diameter
D_o	-	tube outside diameter
L	-	tube length
N_s	-	number of sections

4.4.4 Controller

Controllers consist of a mathematical transformation of input signals to output signals for actuators. In this context the input signal is induced by a temperature sensor and the controllers are of the P, PI or PID-type.

P-controller:

$$u = K_p \cdot e \quad e = T_{ref} - T_w$$

PI-controller:

$$\Delta u = K_p \cdot [(e(i+1) - e(i)) + \frac{\Delta t}{T_i} e(i+1)]$$

PID-controller:

$$\Delta u = K_p \cdot [(e(i+1) - e(i)) + \frac{\Delta t}{T_i} e(i+1) + \frac{T_d}{\Delta t} (e(i+1) - 2e(i) + e(i-1))]$$

Nomenclature:

u	-	controller signal
K_p	-	controller gain
T_{ref}	-	reference temperature
T_w	-	measured temperature
T_i	-	integration time
T_d	-	derivation time
Δt	-	time step

4.4.5 Actuator

The actuator is the engine which actually moves the valve plug.

Mathematical description:

$$\Delta z = \frac{\Delta t}{T_z} \cdot [\beta(i+1) - \beta(i-1)]$$

Nomenclature:

z	-	actuator position
Δt	-	time step
T_z	-	the time it takes the actuator to move from closed to fully open position
β	-	actuator speed direction

4.4.6 2-port valve

The 2-port valve is the component governing mass flow through the system. Control valves are essentially variable fluid resistances.

Mathematical description:

$$\text{Volume flow: } F = \sqrt{\frac{(k_{vs} \cdot f(z))^2 \cdot \Delta p \cdot \frac{\rho_0}{\rho_1}}{1 + (k_{vs} \cdot f(z))^2 \cdot \Delta p \cdot (1-a) \cdot \left(\frac{1}{F_{\max}^2}\right) \cdot \frac{\rho_0}{\rho_1}}}$$

$$\text{Linear valve: } f(z) = \left(1 - \frac{1}{R}\right) \cdot z + \frac{1}{R}$$

$$\text{Quadratic valve: } f(z) = \left(1 - \frac{1}{R}\right) \cdot z^2 + \frac{1}{R}$$

$$\text{Exponential valve: } f(z) = R^{z-1}$$

Nomenclature:

F	-	volume flow
F_{\max}	-	nominal volume flow
k_{vs}	-	volume flow through fully open valve at 20°C and 1 bar pressure difference
$f(z)$	-	valve characteristic
Δp	-	pressure difference of total system
ρ_0	-	density of water at 20°C
ρ_1	-	density of water at actual temperature
a	-	valve authority
R	-	control ratio
z	-	valve position

5 TEST SIMULATIONS

The purpose of the test simulations has been to debug the simulation tools and to give some examples of alternative applications.

5.1 Radiator test simulations

The test simulations are based on three different simulation sequences:

1. Each radiator uses thermostatic valves, and the secondary water inlet temperature is controlled according to figure 5.1, simulation 1. This simulation is used as a reference.
2. Each radiator uses thermostatic valves and the secondary water inlet temperature is controlled according to figure 5.1, simulation 2.
3. Each radiator uses thermostatic valves. One radiator has a decrease in surface area of 20%. The secondary water inlet temperature is increased to satisfy the load demand. See figure 5.1, simulation 3.

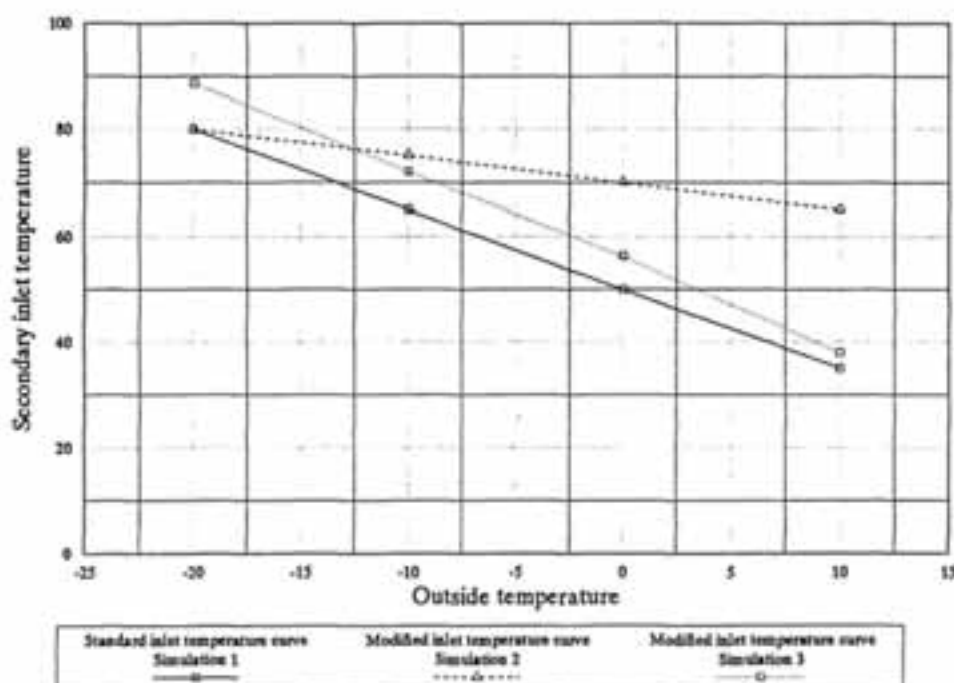


Figure 5.1 Water inlet temperature dependent on outside temperature, simulation 1, 2 and 3.

Each simulation sequence consists of four simulations at various outside temperatures, -20, -10, 0, 10°C. The primary and secondary return temperatures are recorded and figures 5.2 and 5.3 reveal the simulated results.

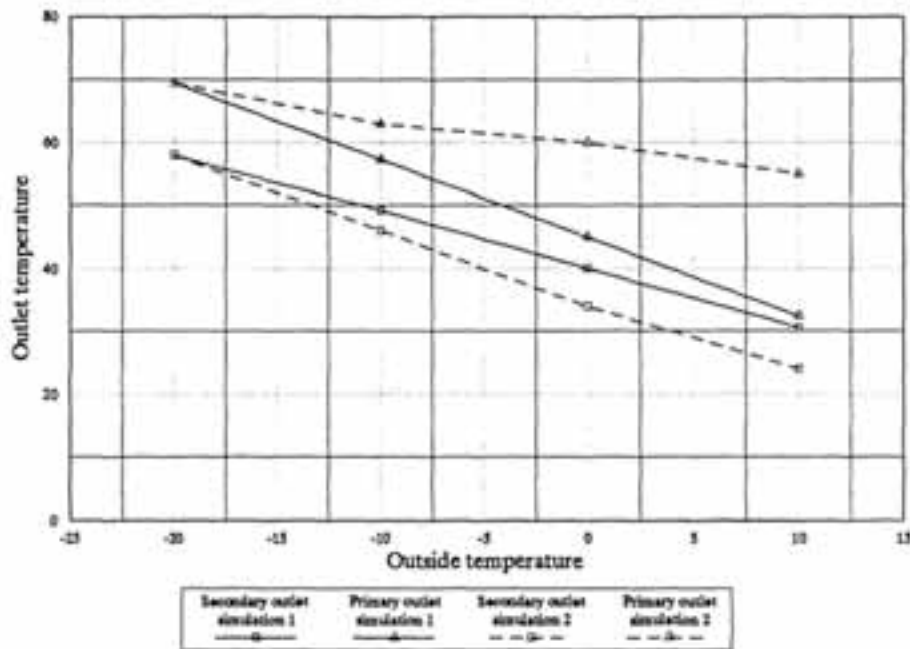


Figure 5.2 Primary and secondary water outlet temperatures in district heating connected radiator system, simulation 1 and 2.

Simulation 1, fig 5.2, is used as a reference simulation, and we find that both the primary and secondary outlet temperatures decrease with increasing outside temperature. In simulation 2 we find that the secondary outlet temperature is at a lower level compared to simulation 1 due to increased logarithmic mean temperature difference (LMTD) in the radiator. The primary outlet temperature in simulation 2 is however at a much higher level compared to simulation 1 due to a decreased LMTD in the heat exchanger. This indicates that the consequence of not using a correct combination between water inlet temperature and outside temperature will decrease the primary water difference.

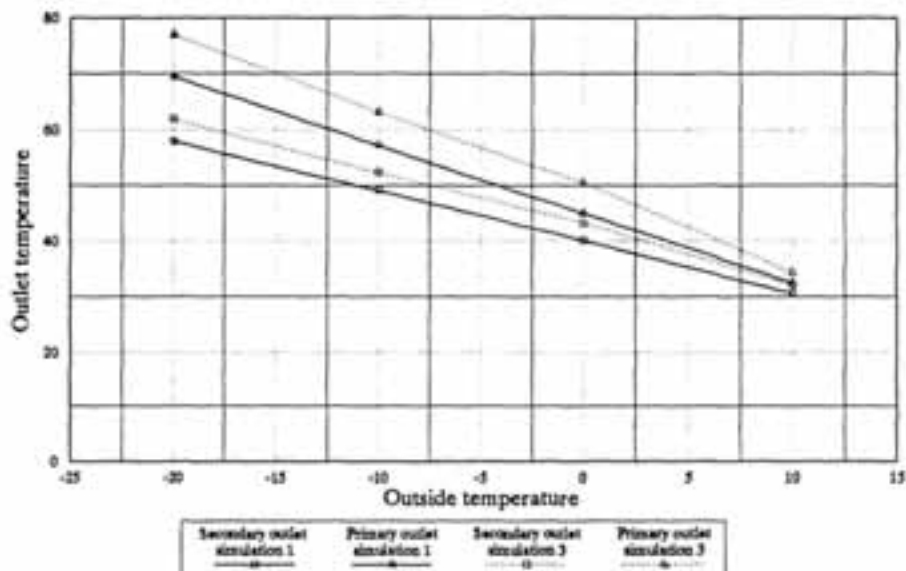


Figure 5.3 Primary and secondary water outlet temperatures in district heating connected radiator system, simulation 1 and 3.

In simulation 3 we find that a decrease in radiator surface area increases the level of both primary and secondary outlet temperatures. The increase in temperature level is most significant at low outside temperature levels.

5.2 Ventilation air system test simulation

5.2.1 Static ventilation air system evaluation

The objective of the test has been to evaluate the influence of using oversized 3-port control valves. Figure 5.4 shows the water temperature difference over the heat coil with two alternative 3-port valves sizes ($k_v = 1.6$ and $3.2 \text{ m}^3/\text{h}$). We find that the temperature difference is considerably decreased when the valve size is increased.

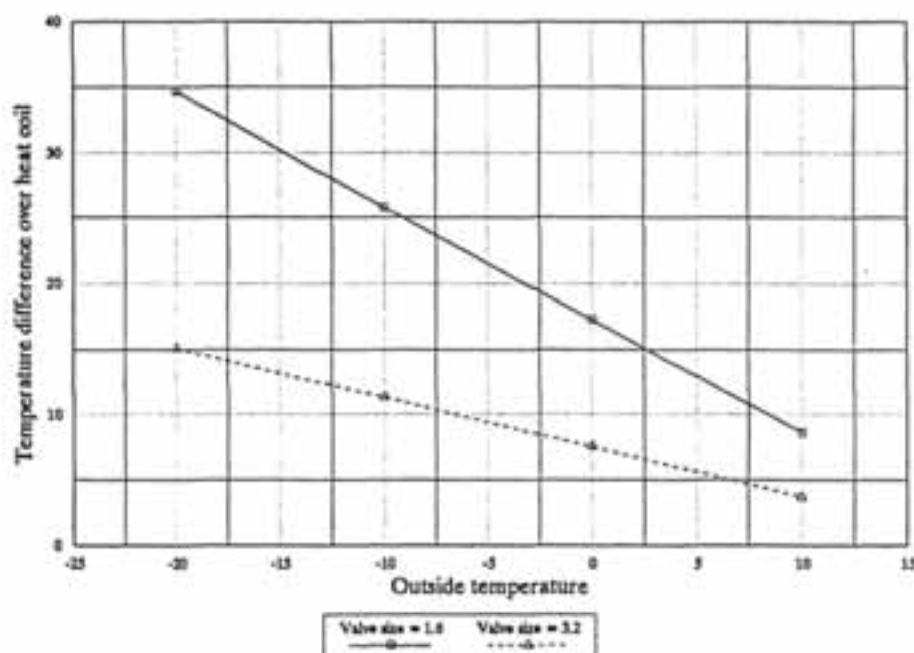


Figure 5.4 Water temperature difference over heat coil.

Figure 5.5 shows the total secondary temperature difference through the system concept, and we find that, in spite of the considerable decrease in temperature difference over the heat coil, the decrease in secondary temperature difference is very small. Due to the increased flow capacity the heat transfer coefficient is increased and "the loss" in total temperature difference is marginal.

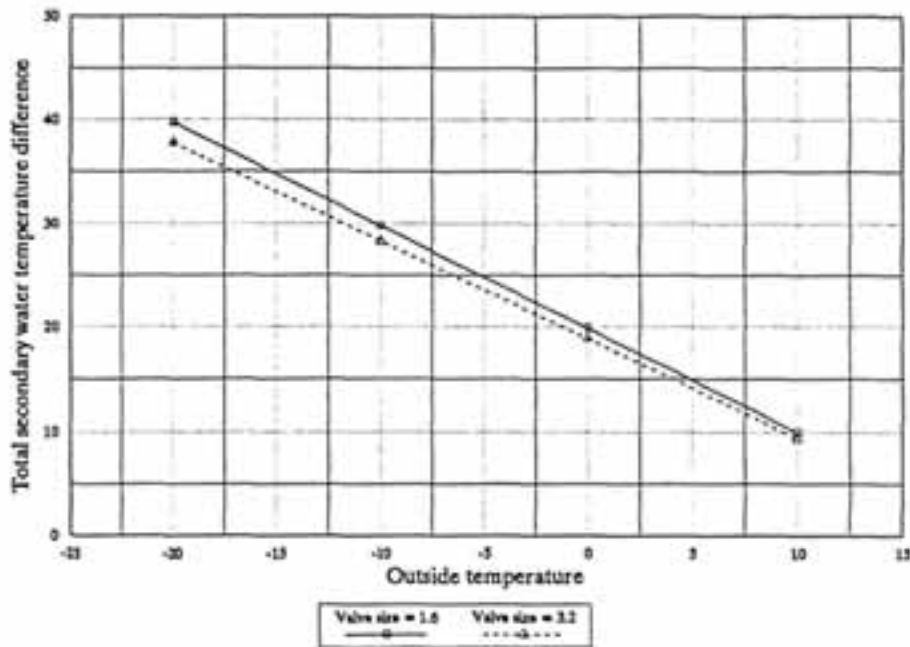


Figure 5.5 Total secondary water temperature difference.

The increase in flow capacity at increased valve size implies that the secondary inlet temperature can be decreased. Figure 5.6 shows the standard and modified secondary inlet temperature curve.

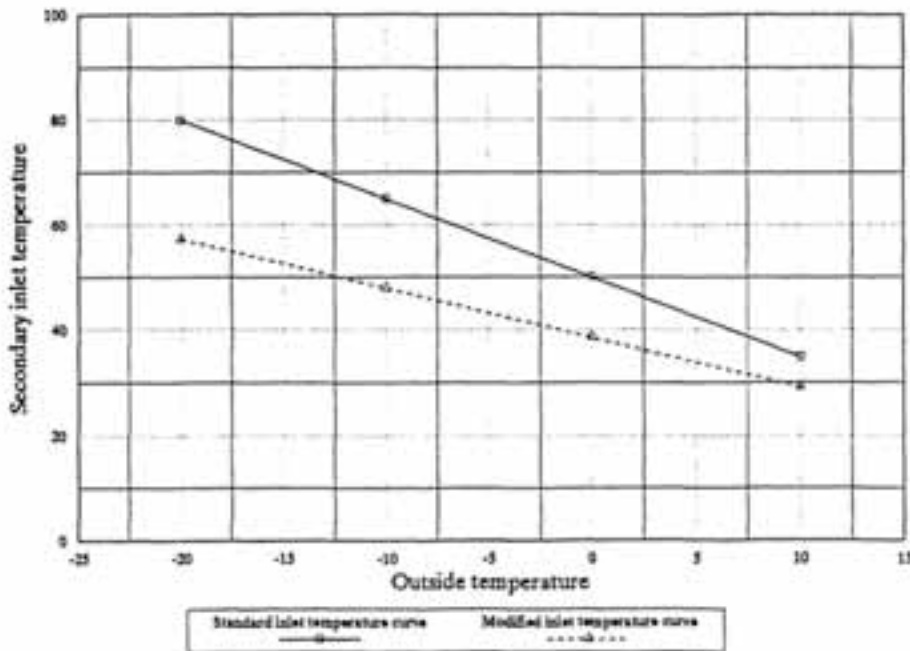


Figure 5.6 Standard and modified secondary inlet temperature curve.

Figure 5.7 shows the primary return temperature dependent on valve size and secondary inlet temperature curve. When the valve size is increased we find a small increase in primary return temperature. However, if the secondary inlet temperature curve is adjusted, we find that

adjusted, we find that the primary return temperature is considerably decreased due to increased LMTD. In overdimensioned systems it is possible to decrease the primary return temperature by adjusting the secondary water inlet temperature curve.

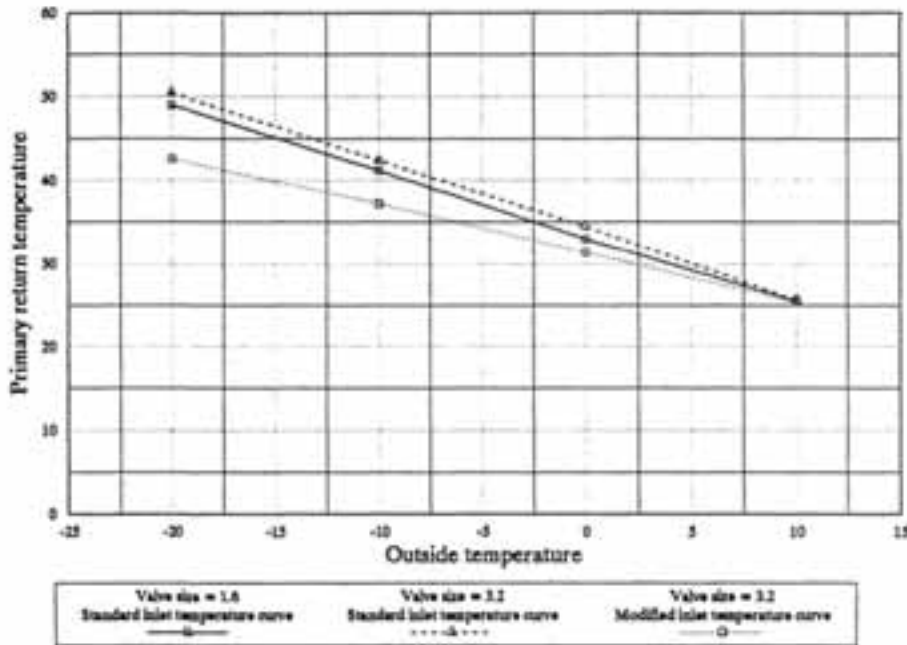


Figure 5.7 Primary return temperature dependent on valve size and secondary inlet temperature.

On the figures 5.1 - 5.7 the results from the test simulation are presented by separated curves for the different temperatures.

From these figures it is somewhat difficult to get a clear overview of the heat-exchange processes that are analyzed. To clarify the results the corresponding water temperatures from the analyses of the heat coil and the radiator system are put together in the figures 5.8 and 5.9.

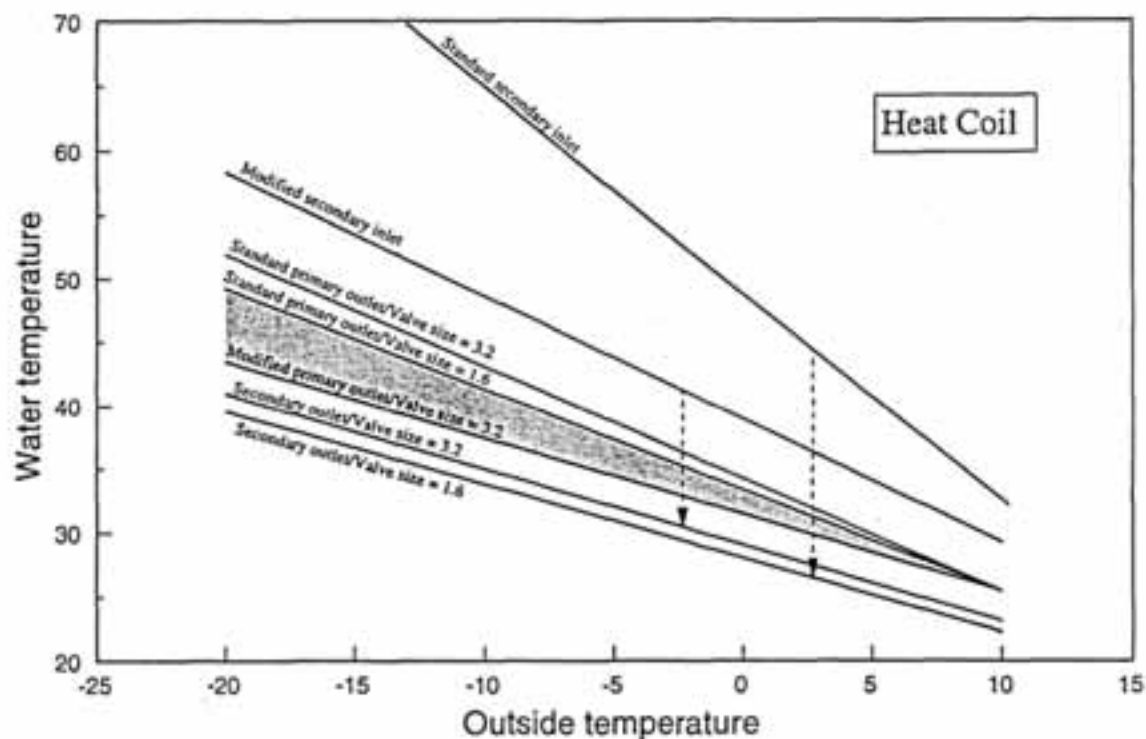


Figure 5.8. Corresponding temperature curves from the Heat Coil analyses.

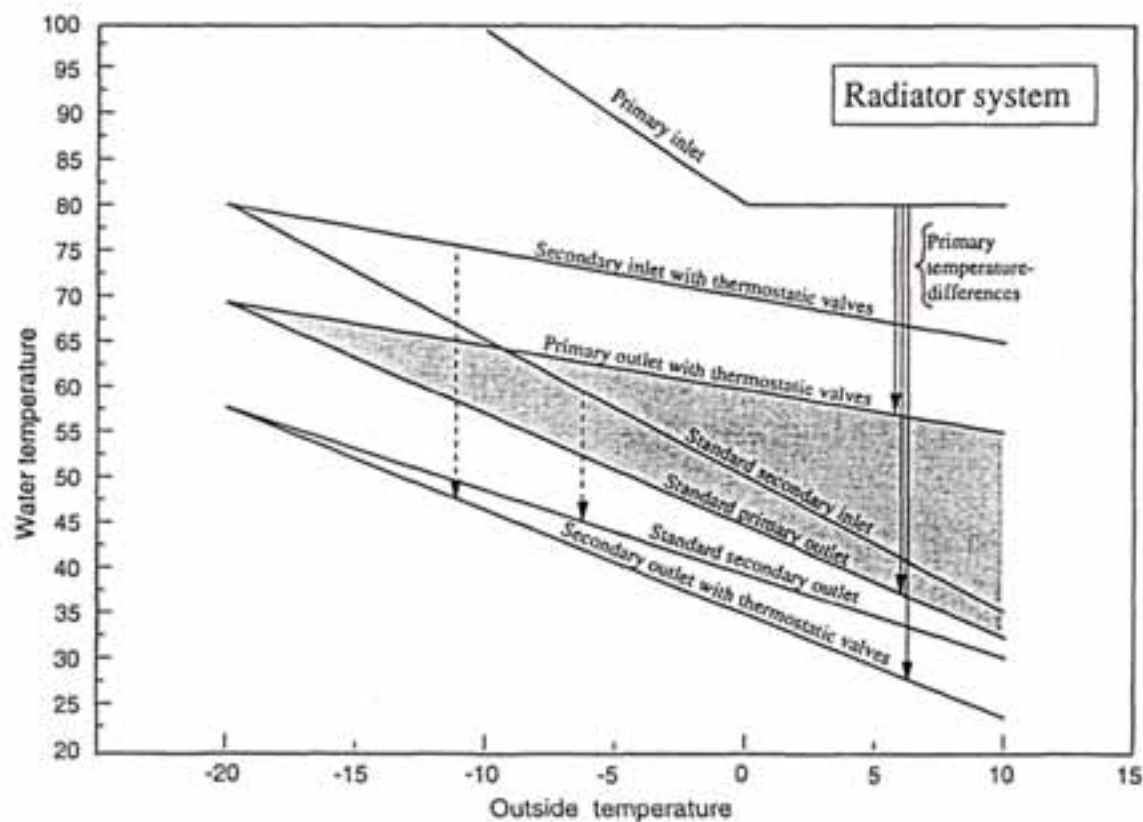


Figure 5.9. Corresponding temperature curves from the Radiator system analyses

From these figures we may draw some conclusions based on the cases that are analyzed in the test simulation:

- * In district heating (DH) systems with indirect connection (heat exchanger), a modified dimensioning of the regulating valve size for the air heat coil together with a modified inlet water temperature to the coil could lower the district heating return temperature approximately 7°C by outside dimensioning temperature of -20°C
- * Using thermostatic radiator valves in DH-systems with direct connection (no heat exchanger) will normally give a lower or equal primary return temperature than radiator systems without thermostatic valves. A typical average lowering of the return temperature could be about 5°C for the total heating season
- * When using thermostatic valves in DH-systems with direct connection you should not try to adapt the inlet temperature to the outside temperature unless this is necessary for some special reasons
- * Using thermostatic radiator valves in DH-systems with indirect connection (heat exchanger) will normally give a higher or equal primary return temperature than radiator systems without thermostatic valves. The average increase in the primary return temperature may very easily be 10 - 15°C for the total heating season
- * When using thermostatic radiator valves in DH-systems with indirect connection you should always have a regulating system that adapts the inlet temperature to the radiators to the outside temperature at every time. The function of the thermostatic valves should only take care of the variation in the heat load caused by other factors than the outside temperature

It should be mentioned here that these test simulations are just examples on how you can use this powerful tool to evaluate the performance of a system that you plan to build.

5.2.2 Dynamic ventilation air heating system evaluation

This section describes a possible dynamic ventilation air heating system evaluation which can be performed with the simulation tool. This evaluation consists of two parts:

- o System control performance dependent on control valve options.
- o General consequence of hysteresis in control loops

System control performance dependent on control valve options

The system control performance is generally dependent on the system configuration and on

the component parameters. The objective of the test has been to evaluate the influence on system control performance by using different control valves and valve characteristics. In the two systems shown the system configuration and the system parameters are equal except from the control valve. In system 1 a 2-port valve is used and in system 2 a 3-port valve is used. Figure 5.10 shows the system configurations.

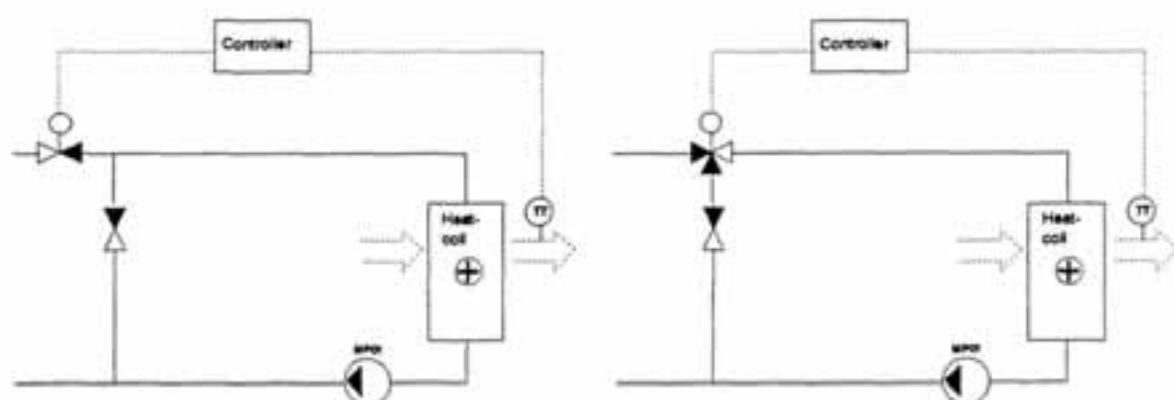


Figure 5.10 Ventilation air heating systems with 2-port and 3-port control valves

The valve characteristic used is either linear or quadratic. Figure 5.11 shows the variation in optimal proportional band for the four alternatives based on step response analysis.

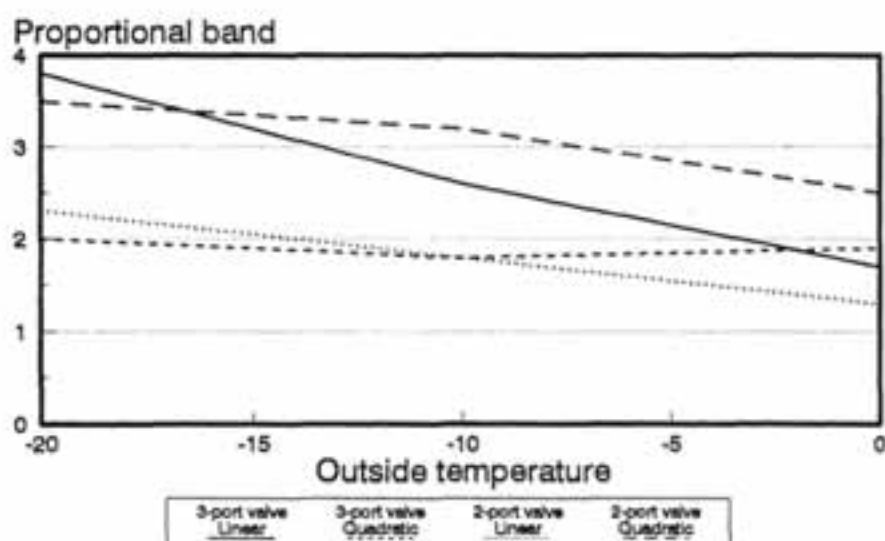


Figure 5.11 Optimal proportional band dependent on control valve parameters and outside temperature.

An optimal proportional band variation is undesirable due to a general decrease in system performance. When the controller is "tuned" the system operates at a certain outside temperature which is random and dependent on weather conditions. The consequence of optimal proportional band variation is a decrease in controller performance at outside temperature levels different from the one the controller was "tuned". On this basis a goal in system design is to choose systems and component parameters which minimize the optimal proportional band variation.

In the systems shown the configuration with 3-port valve with quadratic valve characteristic gives a minimum variation in proportional band level. The other configurations have a variation between 40 and 120 %.

General consequence of hysteresis in control loops

Hysteresis is emphasized upon because the speed with which hysteresis develops is a consequence of system design. Well-designed systems usually result in stable control and minimum wear in valves and actuator couplings. Hysteresis increase with time because of valve and actuator wear and is a consequence of slack in couplings and gears and the electronic dead band in the actuator.

Accuracy is lost with increasing hysteresis due to the progressive problem of exact valve positioning, and the controller output signal has to change a certain magnitude before the stem position is affected.

Figure 5.12 shows simulations of a ventilation air heating system with 2-port valve and various degrees of hysteresis.

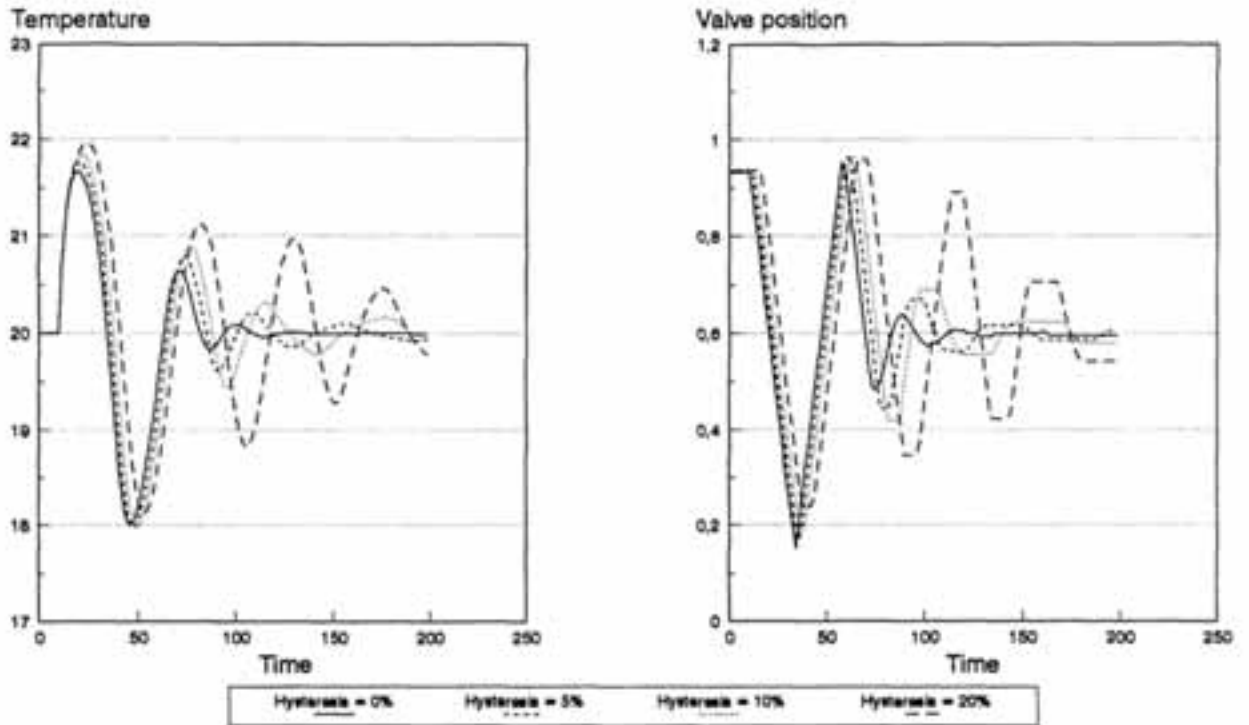


Figure 5.12 Ventilation air temperature stability to variable hysteresis in system with 2-port valve.

The period of oscillation is significantly increased when hysteresis is introduced. Focusing on valve movement it can clearly be seen that hysteresis is the source of a delay effect in stem movement. This delay is the source of increased air temperature fluctuation which is undesirable considering a further increase of hysteresis.

6 REFERENCES

- /1/ Hjorthol E.M., "Optimization of design values in district heating substations by system simulation", Thesis Norwegian Institute of Technology 1990.
- /2/ Kreith F., Black W.Z., "Basic heat transfer", Harper and Row Publishers, 1980.
- /3/ Gummerus P., "Analys av konventionella abonnentsentraler i Fjärrvärmesystem", Thesis Chalmers Tekniska Högskola, Sverige 1989.
- /4/ Pedersen N.E.T., "Radiators varmeavgivelse" Norwegian University of Technology, 1973.

APPENDIX A1

Simulation example.

The intension of the simulation example is to illustrate how the simulation tool can be used in means of changing input data and solving complex problems. The simulation case presented illustrates the importance of minimizing the distance between the 3-port valve and the heat coil to avoid large transport delays and poor operation.

Parameters of importance:

Primary inlet temperature	100 °C
Secondary inlet temperature	80 °C
Air flow	1 m ³ /s - 0.8 m ³ /s
Outside air temperature	4 °C
Inlet air temperature	20 °C

Start the simulation by typing **CHESS3V <CR>** (system with 3-port valves)

Screen picture:

```

SIM version 3.10
A simulation program for dynamic systems
(C) Copyright CAMO A/S
Jarleveien 4, N-7041 Trondheim, Norway

Licence: SINTEF, AVD. FOR VARMETEKNIKK

File name (.DAT).....:

```

Write the name of your datafile **CHESS3V <CR>**

Screen picture:

```

Main command set(Simulation).....:

```

We want to run an initial simulation which is necessary to enable parameter change. Type **<CR>** which makes use of the default parameter (Simulation).

Screen picture:

```

Main command set (Simulation).....:
Solution method (Euler).....:

```

We want to use the Euler solution method; type **<CR>**.

Screen picture:

```
Main command set (Simulation).....:
Solution method (Euler).....:
Time interval (Ti,Tf) ( 0.0 , 0.0 ).....:~
```

Type 0,10 which initiates a simulation of 10 seconds.

Screen picture:

```
Main command set (Simulation).....:
Solution method (Euler).....:
Time interval (Ti,Tf) ( 0.0 , 0.0 ).....: 0,10
Step size ( 0.0 ).....:~
```

Type **0.1 <CR>** which is a convenient step size.

Screen picture:

```
Main command set (Simulation).....:
Solution method (Euler).....:
Time interval (Ti,Tf) ( 0.0 , 0.0 ).....: 0,10
Step size ( 0.0 ).....: 0.1
Simulating.....
|=====|>
# of sample 100
# of stored 100
Main command set (Output).....:~
```

The initial simulation is finished and we are back at the main command set level.

The following part consists of changing simulation parameters.

Type **Data-file <CR>** to enter the data file mode.

Screen picture:

```
Main command set (Simulation).....:
Solution method (Euler).....:
Time interval (Ti,Tf) ( 0.0 , 0.0 ).....: 0,10
Step size ( 0.0 ).....: 0.1
Simulating.....
|=====|>
# of sample 100
# of stored 100
Main command set (Output).....: Data-file
Data file operations (Change).....:~
```

Type **Param <CR>**

Screen picture:

```

MODEL NO   1 IS  EXCITATION 1
MODEL NO   2 IS  HEAT EXCHANGER 1
MODEL NO   3 IS  CONTROL VALVE 1
MODEL NO   4 IS  CONTROLLER 1
MODEL NO   5 IS  PIPE 1
MODEL NO   6 IS  PIPE 2
MODEL NO   7 IS  PIPE 3
MODEL NO   8 IS  PIPE 4
MODEL NO   9 IS  CONTROL VALVE 2
MODEL NO  10 IS  CONTROLLER 2
MODEL NO  11 IS  EXCITATION 2
MODEL NO  12 IS  PIPE 5
MODEL NO  13 IS  HEAT EXCHANGER 2
MODEL NO  14 IS  PIPE 6
MODEL NO  15 IS  VENTILATION DUCT
MODEL NO  16 IS  CONTROL VALVE 3
MODEL NO  17 IS  CONTROLLER 3
MODEL NO  18 IS  PIPE 7
MODEL NO  19 IS  RADIATOR 1
MODEL NO  20 IS  PIPE 8
MODEL NO  21 IS  CONTROL VALVE 4
MODEL NO  22 IS  CONTROLLER 4
NO         23 IS  GLOBAL VARIABLES

```

WRITE MODNO.: (0).....:

The model description at the right refers to figure A1.

By typing the model number and <CR> the model parameters will appear on the screen and can be adjusted by typing the new value and using the space bar. The "Global Variables" contains volume flows and controller output signals besides thermodynamic properties.

We want a primary inlet temperature of 100 °C. From the system description we find that EXCITATION 1 direct the *primary* inlet temperature.

Type 1 <CR>

Screen picture:

```

-      120  INLET TEMPERATURE
      1000  ALTERATION TIME
      120  NEW INLET TEMPERATURE

```

Type 100 and press <SPACE BAR>. The temperature changes from 120 to 100.

Press <SPACE BAR> to return to model menu.

Type 0 <CR> 0 <CR> to return to the main command set.



seconds. We see that both states have stabilized.

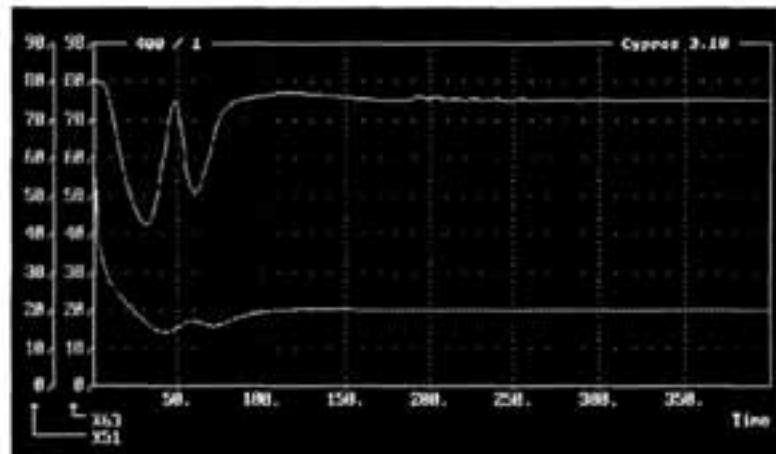
Now its time to start the evaluation process.

Type **0** <CR> **0** <CR> to return to the main command set.

Type **Data-file** <CR> **Update**

<CR> **Oppdat** <CR>. Update and oppdat updates the state and parameter arrays.

Type **Param** <CR> to enter the menu for parameter change.



We want to evaluate the influence of change in air flow from $1 \text{ m}^3/\text{s}$ to $0.8 \text{ m}^3/\text{s}$ in a "normal" system, and in a system with a large transport delay, 10 meter pipeline from the 3-port valve to the heat coil.

We start by evaluating the "normal" system where the pipeline from the 3-port valve to the heat coil is 1 meter.

Type **11** <CR>

Screen picture:

```

-      4      INLET TEMPERATURE
      1000    ALTERATION TIME
      4      NEW INLET TEMPERATURE
      1000    REALTERATION TIME
      1      INITIAL FLOW [m3/S]
      1      NEW FLOW [m3/S]

```

Move the cursor using the arrow keys down to line 2 and type **10** and press <space bar>. This results in a change of inlet air parameters during simulation after 10 seconds.

Move the cursor down to line 6 and type **0.8** and press <space bar>.

The air flow will now change from $1 \text{ m}^3/\text{s}$ to $0.8 \text{ m}^3/\text{s}$ after 10 seconds.

Press <space bar> **0** <CR> **0** <CR> to return to main command set.

Use the default option, (Simulation) and press <CR> to start the first evaluation simulation.

Use the default solution method; (Euler), and press <CR>.

A suitable evaluation period is 300 sec. Type **0** , **300** <CR>

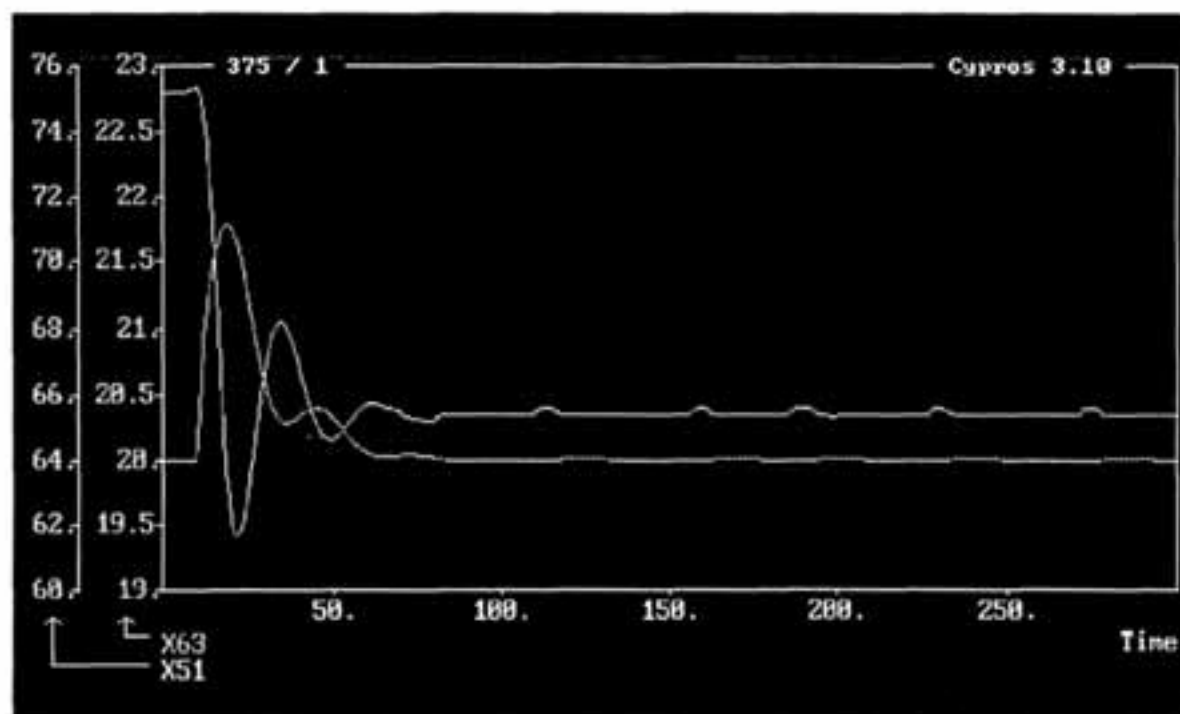
Use the default step size of (0.1 sec.), and press <CR>.

Use the default parameter, (Output), and press <CR>.

Use the default parameter, (Show-Result), and press <CR>
 Use the default parameter, (Y-Variables), and press <CR>
 Use the default Y-variables, x51, x63, and press <CR>
 Use the default parameter, (Separate-Axis), and press <CR>

From the screen picture we see that the inlet air temperature has a temporary increase up to 21.8 °C but stabilize on 20 °C after approximately 60 seconds. The inlet water temperature level decreases from 75 °C to approximately 66 °C due to the decrease in air flow. The figure shows that the control system has no problems in handling the change in air flow.

Screen picture:



Type **0** <CR> **0** <CR> to turn to the main command set.

To create the system with large transport delay we need to change the pipe length of pipe 5 and pipe 6 from 1 to 10 meters. This distance often occur when the 3-port valve is wall-mounted.

Type **Data-file** <CR> and **Param** <CR> to enter the model menu.
 We find that pipe 5 and pipe 6 are models 12 and 14.

Type **12** <CR>

Screen picture:

```

-      1      PIPE LENGTH [m]
      0.027   INSIDE DIAMETER [m]
      0.030   OUTSIDE DIAMETER [m]
      460     WALL HEAT CAPACITY [kJ/kgC]
      7820    DENSITY PIPE [kg/m3]

```

Type **10** and press **<space bar>**.

Press **<space bar>** to return to the model menu.

Repeat the procedure for pipe 6, model 14.

Type **0 <CR> 0 <CR>** to return to the main command set.

Use the default option, (Simulation) and press **<CR>** to start the second evaluation simulation.

Use the default solution method; (Euler), and press **<CR>**.

Use the default simulation period of 300 seconds and press **<CR>**.

Use the default step size of (0.1 sec.), and press **<CR>**.

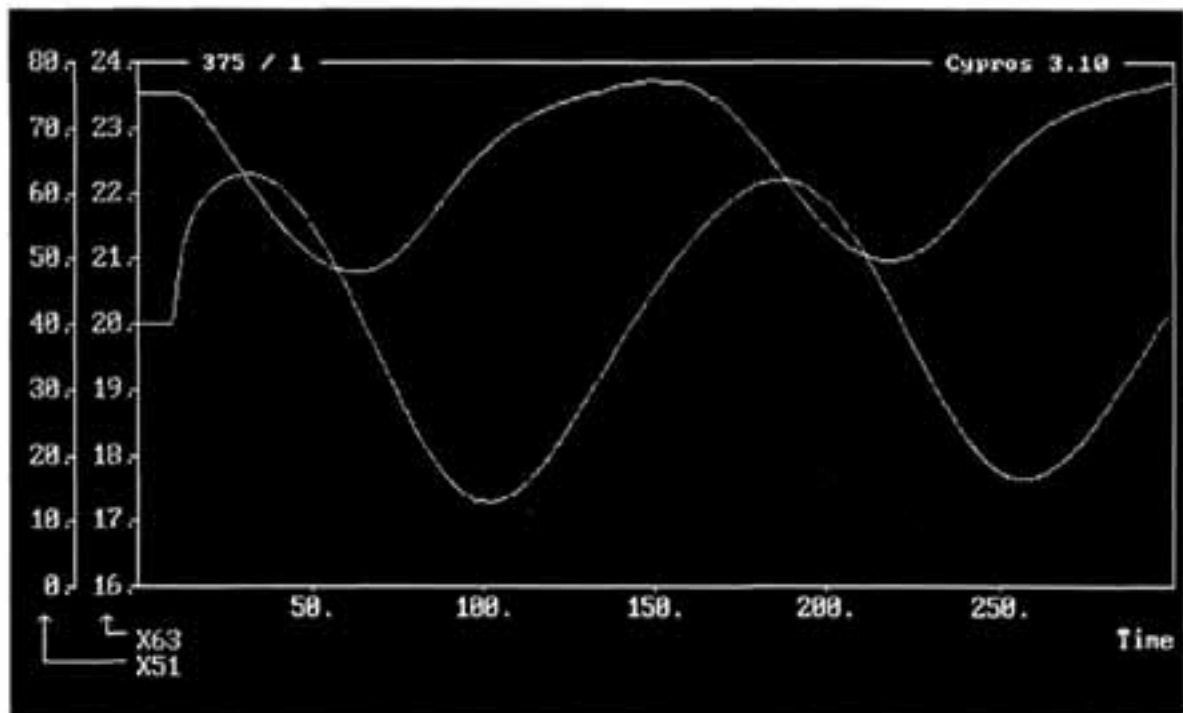
Use the default parameter, (Output), and press **<CR>**.

Use the default parameter, (Show-Result), and press **<CR>**

Use the default parameter, (Y-Variables), and press **<CR>**

Use the default Y-variables, x51, x63, and press **<CR>**

Use the default parameter, (Separate-Axis), and press **<CR>**



The screen picture shows an unstable process where the air and inlet water temperature fluctuates due to a large transport delay. The process can be stabilized by reducing the controller gain and increasing the integration and derivation time, but the control system will then operate very slowly.

Type **0** <CR> **0** <CR> to return to the main command set.

If you want to leave the program, type **E** <CR>.

IEA District Heating

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