Efficient Substations and Installations (1996 N5)

Summary
As part of Annex IV of the International Energy Agency's District Heating and Cooling Project (IEA-DH&CP), a project called **E**fficient **S**ubstations and **I**nstallations (**ESI**) has been performed.

The main objective of the project was to develop more efficient consumer heating systems in commercial buildings, where heating energy is supplied by district heating (DH). The need for more efficient systems has increased in recent years, as low temperature DH is considered to be favourable in a future perspective. The project strategy was to undertake a systematic, theoretical study of the design of consumer heating systems, based on thermodynamic analysis. Then some basic system configurations were chosen which make the best compromises between theoretical goals and practical limitations.

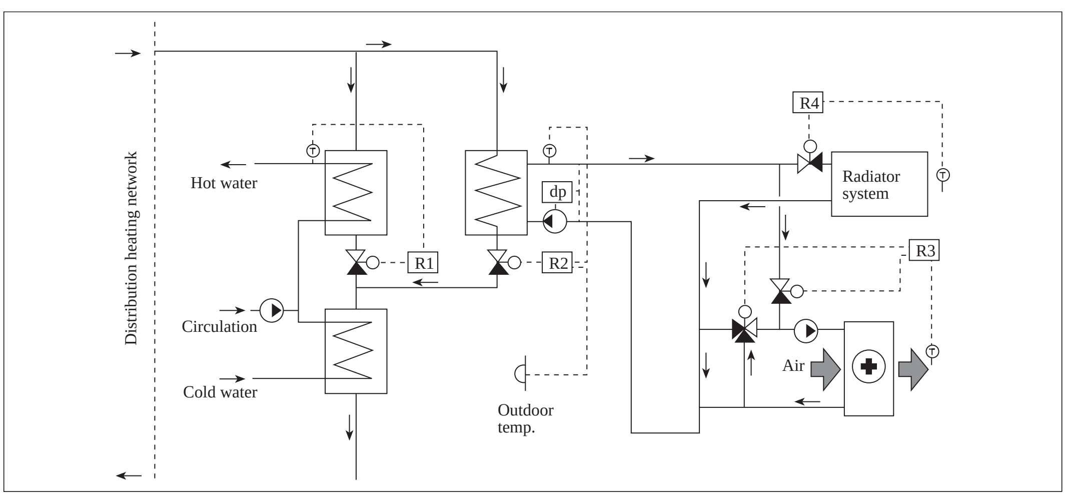
To document the performance of the chosen systems, a simulation tool was needed.
This was done with an extended and improved version of the simulation program called **CHESS** (**C**onsumer **H**eating **S**ystem **S**imulation) which was formerly developed in Annex III of the IEA-DH&CP. The extended and improved version of CHESS is called **CHESS-ESI**.

The theoretical studies lead to the conclusion that the common system, where service water is heated in two steps, has the potential to give the maximum cooling of the DH-water. This basic concept for service water heating was therefore chosen as a part of the new systems.

Three alternative principal system configurations for space heating were evaluated in CHESS-ESI:

System 1 Ventilation heating coil and radiator system connected in parallel on the secondary side of the heat exchanger (Used as "Reference system" in the documentation of the performance of the new systems since this system is common today)
System 2 Ventilation heating coil connected in series with the radiator system on the secondary side (See Figure 1)
System 3 Ventilation heating coil connected in series with the radiator heat exchanger on the primary side

Figure 1. System 2: Ventilation air heating coil connected in series with the radiator system in the secondary side.



From the theoretical studies it was deduced that there should be an optimal secondary supply temperature which would give the lowest primary outlet temperature from the space heating system's heat exchanger. From simulations, the optimal secondary supply temperatures could be found for the actual conditions, as demonstrated for System 2 in Figure 2. The overall conclusion from these simulations is that every individual space heating system in practice has its own optimal "heating curve" which normally is a nonlinear function of the outside temperature.

The simulations showed that for Systems 2 and 3 a small modification of the ventilating heating coil design could significantly increase the cooling of the primary water. Figure 3 shows the cooling of the primary water across the space heating heat exchanger by optimised heating curves and a modified ventilating heating coil design for the three principal systems in CHESS-ESI.

In these simulations we have a conventional high temperature DH-system with 120 °C design temperature and 80 °C primary supply temperature in summer.

Figure 2: Primary return temperature from space heating heat exchangers as function of secondary supply temperature for System 2

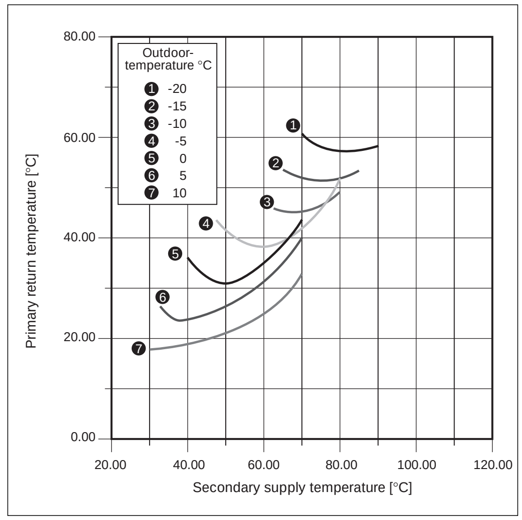
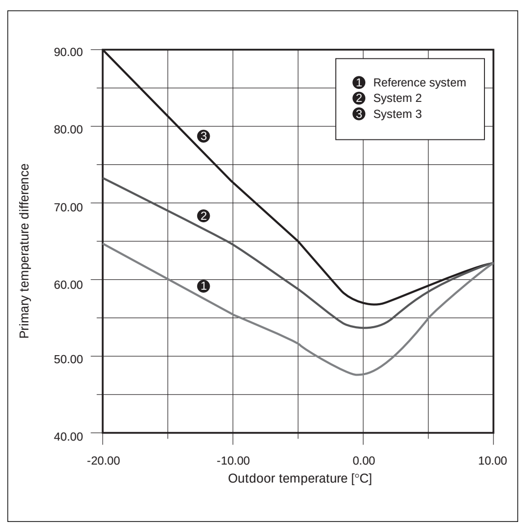


Figure 3: Primary temperature difference for space heating system with optimized heating curves, high temperature DH-system.



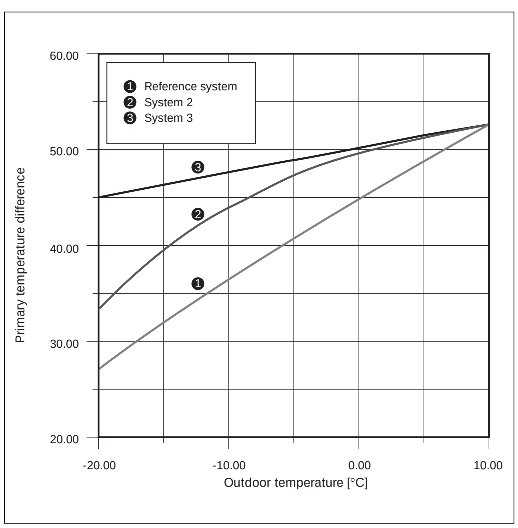


Figure 4: Primarytemperature difference for space heating system with optimized heating curves, low temperature DH-system

Modern DH-systems will normally be designed for lower primary supply temperatures compared with old systems. Figure 4 shows the results for similar conditions as in Figure 3 but now with a low temperature DH-system with a constant supply temperature of 70 °C throughout the year.

In practice, the cooling of the DH-water in consumer installations is a very important factor for the total economy of DH. It will, for instance, increase the capacity of the expensive DH-pipeline system, and reduce the cost of pumping the hot water. The total cooling of the DH-water across the consumer's installation depends to a great extent on the amount and nature of the service hot water consumption in the actual building. The CHESS-ESI simulations were carried out for typical conditions for an office building and a hospital building for the three system configurations.

For the same conditions as in Figure 3 and a two-step system for the service water heating the results for System 2 and 3 respectively show about 11% and 18% increase in the "annual volumetric mean temperature difference" for the office building compared to the traditional "Reference system". The equivalent values for the hospital building for the two systems were about 8% and 13% respectively.

For the cases above, a decrease in the "design primary flow" for System 2 and 3 respectively were found to be about 8% and 17% for the office building and about 4% and 9% for the hospital building compared to the reference system.

Simulations including service hot water were also carried out for a low temperature DH-system. The results of the simulations for the actual systems above, and a constant primary supply temperature of 70 °C, show an increase in the annual volumetric mean temperature difference of about 12% and 16% for the office building and about 8% and 10% for the hospital building, compared with the reference system.

For the low temperature case, the decrease in the design primary flow for System 1 and 2 is more significant than for the high temperature case. The results show a decrease in the design primary flow for System 1 and 2 respectively of about 9% and 21% for the office building and about 13% and 27% for the hospital building, compared with the reference system.

The simulations in this project are done with a two-step system for service water heating. The CHESS-ESI package may also simulate a one-step system for service water heating. This is achieved by setting the area of the preheat-exchanger to zero (see Figure 1). The space heating system can also be simulated with radiator system only. This is achieved by closing the heating coil control valves.

Introduction to the joint report

The main objective of the present work has been to develop more efficient consumer heating systems in buildings where the heating energy is supplied by hot water district heating (DH). The need for more efficient systems has increased in the latest years due to fact that low temperature DH is considered to be favourable in a future perspective. '

The cooling of the district heating water delivered to a building is directly affecting the capacity of the DH network and is one of the most important factors to reduce the total cost of DH. The work in this project has therefore, to a great extent, been focussing on that problem.

In the project Efficient Substation and Installations (ESI) the strategy has been to systematic, theoretical study of design of the consumer heating system based on the thermodynamical grounds. From there some basic system configurations were chosen which presumably make the best compromises between theoretical and practical goals.

To document the performance of the chosen systems a simulation tool was needed. For this purpose it was planned to use an extended and improved version of the simulation program called Consumer Heating System Simulation (CHESS) which was developed and reported in the former Annex III of the IEA-District Heating and Cooling Project.

It was considered that there was a special need for validation of the heating coil model in the CHESS program, and it was decided to do some work on that topic.

From the start it was decided that the ESI-project should be performed as a joint project between SINTEF, LTH and a work group with close connection to the University of Saskatchewan.

On this background and for technical reasons it was found appropriate to make the joint report in the following three parts:

PART I: Performance Analyses of Efficient Substations and Installations.

PART II: Discussion of Low Temperature Substations -motives, state-of-the-art and some key issues for progress.

PART III: Validation of the Heating Coil Model used in the CHESS program.

The extended and improved version of the CHESS is described in part I of the joint report, and the new simulation program is called **CHESS-ESI**.

In the appendix to the joint report you will find a brief introduction to the use of CHESS-ESI.

A diskette with the executive programmes in the CHESS-ESI package may be requested from NOVEM, the operating agent for the IEA -District Heating and Cooling Project, Annex IV.

PART I: Performance Analysis of Efficient Substations and Installations

Introduction

In the search for more efficient consumer heating systems for district heating, a tool to simulate the operation of different system configurations is useful to evaluate the performance. As mentioned previously, the CHESS simulation concept was developed in a former project under the IEA- District Heating and Cooling Project (Hjorthol and Ulseth 1992). To perform the new simulations in the IEA-Efficient Substations and Installation project, a further development of the CHESS concept was needed.
The new simulating tool that is presented and used in the present project is called CHESS-ESI. With this dynamic simulation tool we are able to simulate the complete heating system within a building connected to a district heating network on a ”standard” PC of today.

CHESS-ESI - A computer tool for analysing district heating substations and heating installations

As previously noted, the CHESS consept originated in a former IEA-District Heating and Cooling project reported in Annex III. In this project the concept has been further developed into the simulation tool, CHESS-ESI. The purpose of this development has been the need to simulate the operation of new consumer heating system configurations to test their performance.
The former version of the CHESS program

was limited to representing the space heating system with one fixed system configuration. This was partly due to settings in the source code of the CYPROS equation solver that limited the number of component models, and partly due to the speed of personal computers at the time.

The CHESS-ESI system models include both space heating and hot water preparation. Hence, the number of component models has increased. To do so the source code has been modified. Additionally, the parameter text has been adjusted as an attempt to improve the user interface.

An evaluation of the CHESS program showed that further development of the component models was required. In CHESS-ESI some models are therefore further developed and some are adjusted compared with CHESS. The heating coil model has been specially evaluated in the work by Johnson and Besant (1995), which is found in Part 3 of this report. Their suggestions for improvements have been taken into account in the heating coil model developed for CHESS-ESI.

CHESS-ESI consists of three principal system simulation models. The first is a reference system and two have been developed as attempts to improve the performance of the consumer heating system.

Conclusions

From the discussion of the case studies above it seems reasonable to draw some conclusions that are valid for these system configurations in general.

In district heating substations with indirect connection, the heating curve, which sets the secondary supply temperature should be optimized to give minimum primary return temperature. If a serial connection is used on the secondary side, like in System 2, the optimization is specially profitable due to the sharp optima.

The optimal heating curve is generally not linear. In conventional parallel systems, however, a linear heating curve can be used without any major increase in primary return temperature due to the relatively flat optima.

Due to the difference in return temperatures from the radiator system and ventilation heating coil system, the optimal heating curve will depend on the ratio between the heat loads. This is specially the case when the recirculation coupling is used on the heating coil as in System 1, 2 and 3. Since the return temperature is constant from this connection, it will favour low secondary supply temperatures.

Serial coupling of radiator system and heating coil has a potential to give a considerable increase in primary temperature difference for the space heating system. To maximize the gain from this connection the temperature levels of radiator and heating coil systems need to be harmonized.

If the serial connection is to be used on the secondary side, as in System 2, a lower design supply temperature necessitates a larger heating coil to match the system. When the heating coil is connected in series on the primary side, as in System 3, the design supply temperature for the heating coil can be allowed higher.

The improved return temperature from the heating coil coupling is more profitable for the serial coupled systems than for the conventional system in parallel. For the serial coupling on the primary side, the return temperature has direct influence on the primary return temperature. Since the marginal costs of decreasing the return temperature from the heating coil are small, the serial connection provides a cost efficient way to maximize the temperature difference.

The annual average performance of the district heating substation can be considerably improved by introducing a serial connection between radiator and ventilation air heating system.

Improvements on the space heating system are most profitable for buildings with low service hot water consumption. For buildings with high hot water consumption, the primary water can be cooled against the cold service water temperature.

The design flow from the substation is decreased by using the serial connection. For low temperature systems with constant primary supply temperature, the potential decrease in design flow is considerable. For the simulated low temperature case the design flow was reduced in the range 20% to 30% compared with the Reference system.

For most systems, the return temperature from the space heating system will be sufficiently high at design conditions to give a preheating of the service hot water that reduces the design flow with a two-step hot water preparation scheme.

PART II: Discussion to Low Temperature Substations : Motives, State-of-the Art & same Key Issues.

Objective

Substations provide the interface between district heating (DH) networks and internal distribution systems in buildings. This part report indentifies some types of technological solutions which have favourable thermodynamic properties, i.e. they are in accordance with an overall move in DH practice towards operation with 1ow network temperatures.
The substation types considered here are modifications of well-established heat exchanger assembly types found in Scandinavian low-temperature hot water DH networks. This tradition has also been the starting point for an IEA-study performed at NTH/SINTEF in Trondheim, Norway, to which this work paper is related.
Before entering into the discussion of the selected technological solutions, the basic premise of low-temperature solutions is discussed, in order that the focus of interest is seen in a proper perspective.

Motives for low temperature operation

There are many arguments in favour of low DH network temperatures. As a first classification the following main arguments can be listed:

1. Improved generation plant performance
2. Reduced heat losses
3. Reduced circulating water flowrate (at lower return water temperature)
4. Cheaper pipeline technology

Low network temperatures can be achieved by a combination of various choices and measures. Some of the associated decisions may cause increased investment cost, while other decisions may result in lower network temperatures without added cost. For instance, network temperatures can be lowered by installing bigger radiators in connected buildings, a measure which clearly will increase investment costs. In contrast, more thermodyanically efficient substation connection schemes may result in lower network temperatures without necessarily calling for more expensive equipment. Ultimately, of course, investment costs will increase below certain network temperatures, so that a trade-off must be made when deciding on the appropriate temperature level.

Below, each of the 4 main attractions listed above will be commented on shortly. It will be seen that in some instances arguments pertain both to forward and return temperatures. In other cases, a certain argument is clearly linked to, either a low forward temperature, or a low return temperature.

Ad 1 (Improved plant performance):
The strongest argument in favour of low network temperatures probably is that low network temperatures can be utilized for improved CHP plant performance. In the next section this fact will be dealt with separately, along with temperature considerations for centralized heat pump plants.
Even with heat-only generation, however, there may be benefits. A particularly interesting instance of this occurs when temperatures become low enough to make recovery of latent heat from combustion gas water vapour possible. Depending on the sort of fuel and the type of generation plant, this becomes feasible at temperatures below typically 40 – 60o C. Such a facility, which is primarily made possible by a low DH return temperature, may result in a boiler efficiency in excess of 100%, based on the lower calorific value of the fuel, as is customary in Europe when specifying boiler efficiency.

Ad 2 (Reduced heat losses):
For a given DH network operating at varying water temperature level, as a first estimation it can be assumed that heat losses are proportional to the difference between the ambient temperature and the arithmic mean of the forward and return water temperatures.

When assessing variations in heat losses at different temperature levels in a design situation, things become a little more complicated, although as with differing operating temperatures the general tendency will be that lower temperatures cause reduced heat losses.

If tf is lowered at constant t, the associated increased flowrate for a given heat load requires bigger pipeline diameters to restrict pressure losses. This in turn will increase the surface area of the pipes. In the extreme, the net result could be a higher heat loss.

Ad 3 (Reduced water flowrate):
If the return temperature is lowered, e.g. due to better cooling of DH water passing substations, the circulating flowrate becomes smaller, for a given forward temperature and for a given heat load. This will reduce pumping costs, due to smaller pressure drops in pipelines.
The economic value of such reduced pumping costs will depend very much upon the type of DH network. Even in networks serving big cities the pumping power demand may be no greater than a fraction of a percentage of the heat load served, typically representing 10% of the size of the heat losses. In such a case the economic value of reduced pumping power will be only margina1.
However, in long transmission lines pumping power demand may amount to several percent of the heat load, in which case a reduced pumping power becomes more significant from an economical point of view.
Apart from reduced pumping costs there may be further benefits to achieve from reduced flowrates because of better primary water cooling. When in a given system distribution pipes are already utilized to a maximum, better primary water cooling in buildings already connected to the network can create possibilities for connecting further buildings, without installing new distribution pipeline capacity.

Ad 4 (Cheaper pipeline technology):
In classical optimization studies of DH network temperatures, specific investment network costs for pipes were usually being related only to the pipe diameter, while the temperature in itself was considered to have only minor influence on pipeline investment costs. The influence of the forward temperature on the costs would only be indirect in that a higher forward temperature for a constant return temperature would reduce the flowrate and thereby the diameter (for

given pressure losses).
This way of representing pipeline investment costs in optimization models is reasonable when the classical type of mains technology can be presupposed, i.e. pipes are installed in concrete ducts surrounded by mineral wool thermal insulation and are allowed to perform free thermal expansion.
Costs for modern plastic-shielded, bonded polyurethane insulated pipes, and other types of mains technology, in contrast tend to become lower when operating temperatures are 1owered for a given pipe dimension.

PART III: Validation of the Heating Coil model used in the Consumer Heating System Simulation Program

Summary
This report is concerned with the design and performance of typical air-heating coils used in buildings supplied by a district heating system. First the method of analysis and design for typical finned-tube heat exchanger coils is presented, and measured data is compared to simulation results. Uncertainties in the heat rate of less than 5% are expected.
Second the existing CHESS program heating coil model is reviewed and compared with the validated simulation model coil simulation results. If the CHESS model is modified to model more accurately the heat exchange processes in a typical coil, it shows good agreement with the U of S simulation program. The current assumed values of heat transfer coefficients, air side heat transfer area, and air volume are not the same as calculated using the U of S simulation model. A simulation program has been produced that will calculate the input values required in the CHESS model for a given heating coil design. It is shown that if corrected values are not introduced as input data for the CHESS program, errors of up to 50% can occur in the overall heat transfer coefficient.
Finally, an optimized heating coil design based on minimizing the Life-Cycle Cost of the heating coil has been determined.
This design has been compared to a conventional heating coil design to show the opportunities available using an optimal design. This optimized coil design resulted in a coil selection that was 65% more expensive, but the system Life-Cycle costs were more than 4 times smaller. The main benefit of using a better designed heating coil is that liquid flow rates can be reduced which is beneficial to the building owner in lower pumping costs, and beneficial to the District Heating utility which would also see the benefit of lower pumping rates.

Introduction
The purpose of this report is to validate the heating coil model in the CHESS program developed by SINTEF for the purpose of dynamic simulation of building HVAC systems connected to a district heating system. A simple 3 cell model using basic energy equations is used in the CHESS program to simulate a heating coil.

The problems involved in the incorporation of a heating coil into the dynamic program is that the input values (flow rates, temperatures, fluid and heating coil mass and volumes) must he easy to specify. Also the mathematical description of the heating coil must not be too complex in the CHESS program.

This report validates the use of the heating coil model used in the CHESS program by comparing results to a steady state simulation model developed at the University of Saskatchewan (U of S). There are four distinct steps in the validation process.

1. The simulation program developed at the U of S is compared to monitored results to show that the model used is accurate when compared to actual finned, staggered-tube heat exchangers.
2. A conventional designed heating coil

specified by a manufacturer to meet the requirements of the simulation example shown in Appendix A of the CHESS manual is used as the basis for comparison of the input values.

3. The CHESS program heating coil model is compared to the simulation results from the University of Saskatchewan using input values calculated from the U of S program.
4. An optimized heating coil design is found for minimum Life-Cycle Cost at the same design conditions as used by the manufacturer for a conventional heating coil design. This optimum heating coil design should provide the most economical design for the building owner.

Conclusions

It is apparent that the model used in the CHESS program is valid only if the correct heating coil input values are used. A validated simulation program has been developed that produces the required input values needed for a simulation in the CHESS program.

The geometric parameters required in the CHESS program can be calculated knowing the dimensions of the heating coil being used in the HVAC system.

The dimensions that are required are:

- Height of the heating coil,
- Width of the heating coil,
- Longitudinal tuhe spacing,
- Transverse tube spacing,
- Tube outer diameter,
- Tube inner diamter,
- Fin spacing,
- Fin thickness,
- Fin wave depth, if wavy fins are used.

The other input values that are required are:

- Air flow rate Liquid flow rate
- Glycol concentration for freeze or burst protection
- Inlet air temperature, pressure and humidity
- Inlet liquid temperature.

The CHESS program model appears to accurately simulate a heating coil at steady state conditions as long as the correct input values are used. The current assumptions used as input values in the CHESS model will lead to significant differences in the results in most cases. The calculations of air volume, and liquid and air side heat transfer coefficients are not accurate using the current assumptions and will lead to the largest errors.