Modelling, simulating and optimizing boiler heating surfaces and evaporator circuits

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Abstract

A model for optimizing the dynamic performance of boiler have been developed. Design variables related to the size of the boiler and its dynamic performance have been defined. The object function to be optimized takes the weight of the boiler and its dynamic capability into account. As constraints for the optimization a dynamic model for the boiler is applied. Furthermore a function for the *value of the dynamic performance* is included in the model. The dynamic models for simulating boiler performance consists of a model for the flue gas side, a model for the evaporator circuit and a model for the drum. The dynamic model has been developed for the purpose of determining boiler material temperatures and heat transfer from the flue gas side to the water-/steam side in order to simulate the circulation in the evaporator circuit and hereby the water level fluctuations in the drum.
The dynamic model has been developed as a Differential-Algebraic-Equation system (DAE) and MATLAB has been applied for the integration of the models. In general MATLAB has proved to be very stable for these DAE systems.
Experimental verification has been carried out at a full scale plant equipped with instrumentation to verify heat transfer, circulation in the evaporator circuit and water level fluctuations in the drum.

Keywords: Optimization of dynamic boiler performance. Dynamic boiler modelling and simulation, heating surfaces, circulating evaporator circuits, drums, DAE and MATLAB. State of the art - Dynamic boiler modelling and simulation.

1 INTRODUCTION

Boilers have been developed and utilized over the past 250 years and have, during the years, been subject to many different studies analyzing their performance and dynamic behavior - a detailed survey of the studies carried out within the area of *Boiler Modelling and Simulation* is given in Appendix B. So, with this background: Why is it still interesting to analyze boilers? First of all boilers are still being applied for new purposes, related to change of fuels, increased requirements with respect to emissions, new inventions within areas like water-chemistry, materials, etc. Secondly as the market competition increases, boilers are being

designed closer and closer to the limit, i.e. better knowledge about dynamical behavior is required. As a result of the liberalization/deregulation of the energy markets, where new opportunities for selling or buying energy arise, more focus is put on the dynamic performance of the boilers.
A dynamic model has been developed for the analysis of boiler performance. MATLAB has been applied for integrating the models, which have been formulated as Differential-Algebraic Equation systems (DAE's).
Increased requirements, with respect to dynamic performance, have a built-in contradiction: Both natural circulating and once-through boilers need a reservoir for absorbing shrinking and swelling during the dynamic operation of the boiler (e.g. start-up), on the one hand, to be able to absorb the fluctuations within the boiler a large reservoir is required/desirable. On the other hand, the material thickness in a pressurized vessel (the reservoir) is approximately proportional to the diameter, i.e. the higher pressure, the larger material thickness. However the allowable temperature gradients for the pressurized vessel decrease as the wall-thickness increases (the stresses in the boiler material related to the temperature gradients are approximately proportional to the square of the material thickness). To optimize the boilers dynamic performance a model utilizing the dynamic model to define constraints has been developed. For the optimization model design variables related to the size of the boiler (i.e. weight) and to its dynamic performance (i.e. load gradient) have been defined. The defined constraints are related to the maximum allowable gradients (i.e. $\frac{dP_{boiler}}{dt}$). The object function to be minimized is defined as a *cost function*, i.e. it includes the cost of the boiler and a *quantification* of the boilers dynamic behavior.

This dynamic modelling and the described optimization challenge are the main topics of the Ph.D. project being written by the author.

2 MODELLING

A dynamic model for the boiler has been developed. To simplify the model it has been split into 3 sub models:

- Heating surface
- Evaporator Circuit
- Drum

The overall model can be seen in Figure 1.

The developed model is described in details in [46] & [45] and further description shall not be given here.

3 EXPERIMENTAL VERIFICATION

For verifying the model a full scale boiler plant has been equipped with extra instrumentation for measuring circulation numbers etc. The boiler is an Aalborg Industries A/S [1] waste heat recovery boiler located after a gasturbine - type MISSION^{TM} WHR-GT. The gas turbine is a LM 2500+ from General Electric - see [37]. The plant was installed at a cruise liner (*Coral Princess*) (see Figure 2) being built at the Chantiers de l'Atlantique shipyard in France, and the tests were carried out during the commissioning and testing of the plant.

The tests were carried out on a full scale plant which means that *true* data with a minimum of errors could be measured[2]. The disadvantage of this approach is a very limited freedom with respect to carry out tests (e.g. start-up, load changes, shut-down etc.). For the actual boiler plant it was only possible to carry out tests for a few days. The data from the measurements are being verified against the developed model.

[2] The alternative would have been to build a relatively small laboratory plant. The advantage of this model is a large degree of freedom with respect to carrying out tests. The disadvantage would be relatively large errors due to boundary effects.

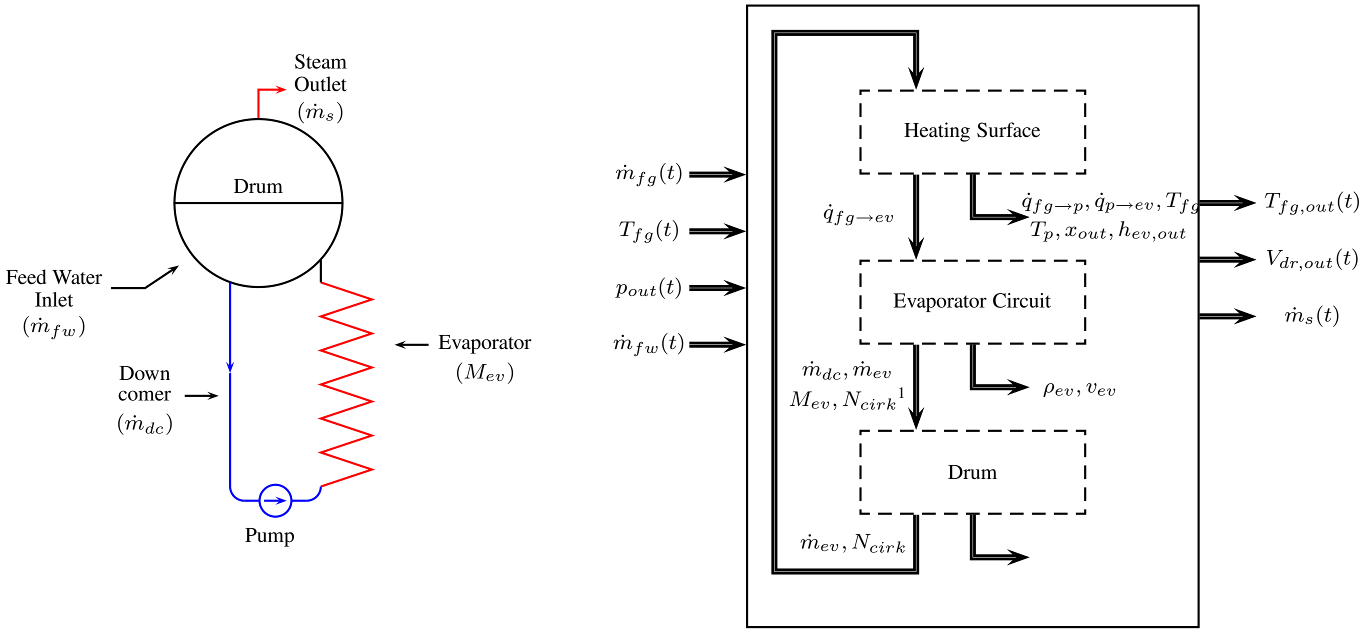

Figure 1: Sketch of water tube boiler and overall model for modelling and simulation of a water tube boiler - including dataflow between the sub-models.

Figure 2: Coral Princess at sea and boiler installed on ship.

4 OPTIMIZATION

As mentioned the focus on dynamic boiler operation is steadily increasing and due to the built-in contradiction - see section 1 - it is important to include the dynamic operation of the boiler plant in the design phase. The first step in the optimization procedure is to define the *design variables*. For the actual problem the *boiler size* and the *load change gradient* have been chosen, these variables are given as:

$$\mathbf{X} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \frac{dP_{gt}}{dt} \\ V_{boi} \end{bmatrix} = \begin{bmatrix} Gas\ Turbine\ Load\ gradient \\ Volume\ of\ boiler \end{bmatrix}$$

To optimize the design of the boiler plant taking its dynamic performance in consideration the following cost function (*objective function*) has been defined:

$$F(\mathbf{X}) = F_{weight} + F_{dyn\ operation} + F_{cons} \tag{1}$$

F_{weight} is the contribution to the cost function from the weight of the boiler - it is presumed that $F_{weight} \propto weight\ of\ the\ boiler$, where the proportionality factor is the specific price of the boiler material. As shown in [45] $F_{weight} \propto (p_{int},\ V_{boi},\ \frac{1}{\sigma_{all}})$.

F_{dyn} is the quantification of the boiler plants ability to operate dynamically. It has only been possible to find a very limited number of data for the quantification[3]. As the cost function is defined as a *penalty function* to be minimized F_{dyn} must posses the characteristic that the higher allowable load gradient for the boiler plant the lower value of F_{dyn} (i.e. a decreasing function). Another characteristic of F_{dyn} is that the function must have asymptotic behavior at very low allowable gradients and at very high allowable gradients. F_{dyn} is only defined for allowable gradients above a certain level[4] As a maximum for F_{dyn} at very low allowable - $F_{dyn,max}$ is approached.

As the allowable gradient increases the *penalty function* decreases until it asymptotic approaches $F_{dyn,min}$.

As a function possessing the above described characteristics, the following function has been defined:

$$\begin{aligned} F_{dyn} &= F_{dyn,\,max} - (F_{dyn,\,max} - F_{dyn,\,min})\cdot \\ &\frac{2}{\pi}\cdot\ arctan\left[k\cdot\left(\frac{dP_{gt}}{dt} - \frac{dP_{gt,min}}{dt}\right)\right] \end{aligned} \tag{2}$$

This means that F_{dyn} has the following graduation - see Figure 3.

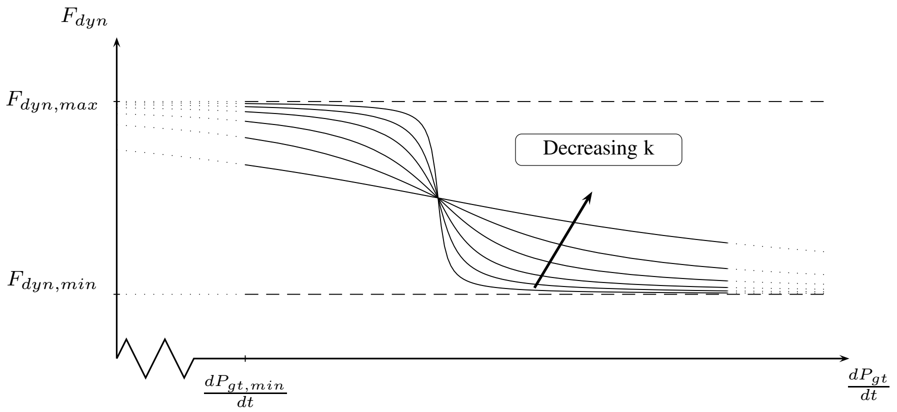

Figure 3: Quantification of dynamic plant operation.

The last term in $F(\mathbf{X})$ is F_{cons}. This term covers terms related to the boiler plants consumption during dynamic operation of it. It is presumed that this term is constant, i.e. $\frac{dF_{Cons}}{d\mathbf{X}} = 0$.

The last step in the optimization procedure is to define the *constraints for the problem*. The following constraints have been defined:

- constraints related to the dynamic operation of the boiler - see section 2
- constraints related to *allowable temperature gradients* in the boiler material - see Figure 4
- constraint related to the required *steam space load* - see Figure 5

[3]Normally the requirements with respect to dynamic performance has been e.g. *the plant must be able to start-up from cold within 60 minutes* or *the plant must be able to operate with a load gradient being minimum 20 % per. minute.*

[4]It would not make sense to have a boiler plant that could only be operated with extreme low allowable gradients.

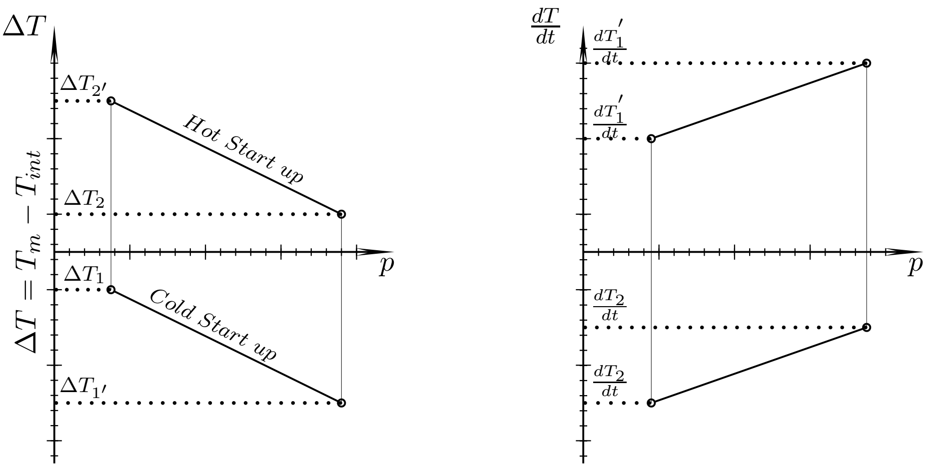

Figure 4: Allowable spatial gradients and allowable time gradients [50].

During dynamic operation of the boiler shrinking and swelling of the water in the drum (i.e. *the reservoir*) occurs, as the water level in the drum only is allowed to fluctuate between e.g. 40 % and 60 % of the the total drum volume (50 % being *Normal Water level*) this constraint define minimum drum size requirements for a given load gradient on the gas turbine.

As the load on the boiler is increasing or decreasing the boiler material will expire certain temperature gradients, the greater wall thickness, the more critical is the temperature gradient. For most boilers the material in the drum will be the most critical. The allowable temperature gradients, which are both gradient with respect to time (i.e. $\frac{dT}{dt}$) and with respect to spacial coordinate in the material (i.e. $\frac{dT}{dx}$) are calculated according to [50].

The last constraint on the dynamic operation of the boiler is the required *steam space load*, this is a requirement ensuring that the steam quality is always within the acceptable range with respect to salt content etc. As steam is continuously transported from the drums water level surface the *carry over* (i.e. the amount of water being carried with the steam), which give coarse to the unacceptable salt content in the steam, will increase above the acceptable level - see [52].

The constraints related to the allowable temperature gradients in the material can be seen in Figure 4 and the constraints related to *steam space load* can be seen in Figure 5.

5 CONTROL PHILOSOPHIES

Another important parameter for the optimization is the *Feed Water control philosophy*. For the time being two philosophies have been analyzed:

- on/off feed water control - see Figure 6(left).
- normal 1-point feed water controller - see Figure 6(right).

For the *on/off feed water controller* it has been defined that the feed water is to be controlled within the range 40 % - 60 % of the drum volume (50 % drum volume correspond to normal water level). If the water level in the drum during dynamic operation drops below 40 % of normal water level the feed water valve opens fully[5] and maximum amount of feed water is supplied to the boiler (i.e. the drum). When the water level rises above 60 % of normal water level the feed water valve closes.

[5]The actual amount of feed water is controlled by the design of the feed water pump system. Normally 110 % full load.

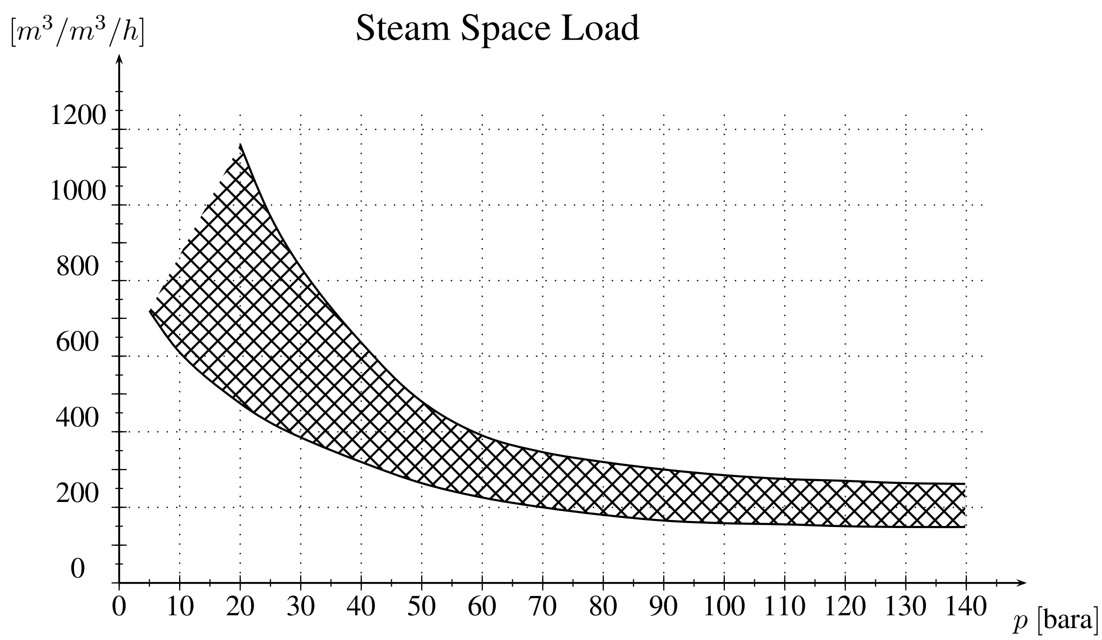

Figure 5: Steam space load, i.e. allowable steam production $[m^3/h]$ per unit steam volume $[m^3]$ in the drum, i.e. volume above water level.

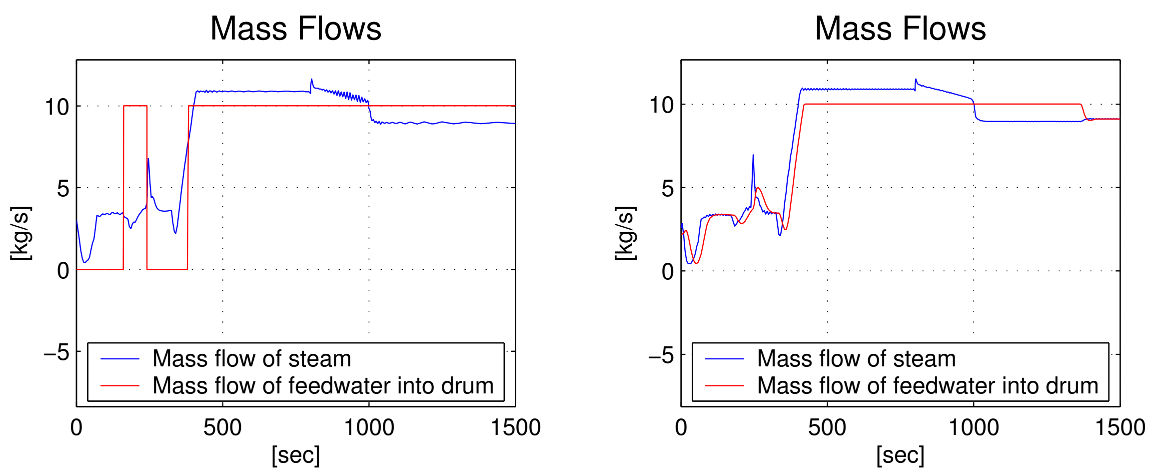

Figure 6: Feed water control philosophies. Left: On/off controller; Right: proportional controller.

The 1-point feed water controller is a traditional proportional controller, where the amount of feed water supplied to the boiler is proportional to the actual water level in the drum[6].

Another important aspect of the overall control philosophy is how to built-up pressure on the boiler. As the most critical part of the boiler typically is the drum that is exposed to saturation conditions, the drum will experience temperature gradient ($\frac{dT}{dt}$) equal to $\frac{dT_{sat}}{dt}$. Normally either the pressure gradient will built-up according to pre-defined function or the steam flow from the boiler will be controlled according to pre-defined function. If the first mentioned philosophy is applied the steam mass flow from the boiler will fluctuate to meet the specified pressure gradient. And if the second philosophy is applied, the pressure on the boiler will

[6]More advanced feed water controller, e.g. 2- and 3-point controller taking the actual feed water and steam flow into consideration are normally not applied for smaller boiler - a more detailed description of these can be found in [27]

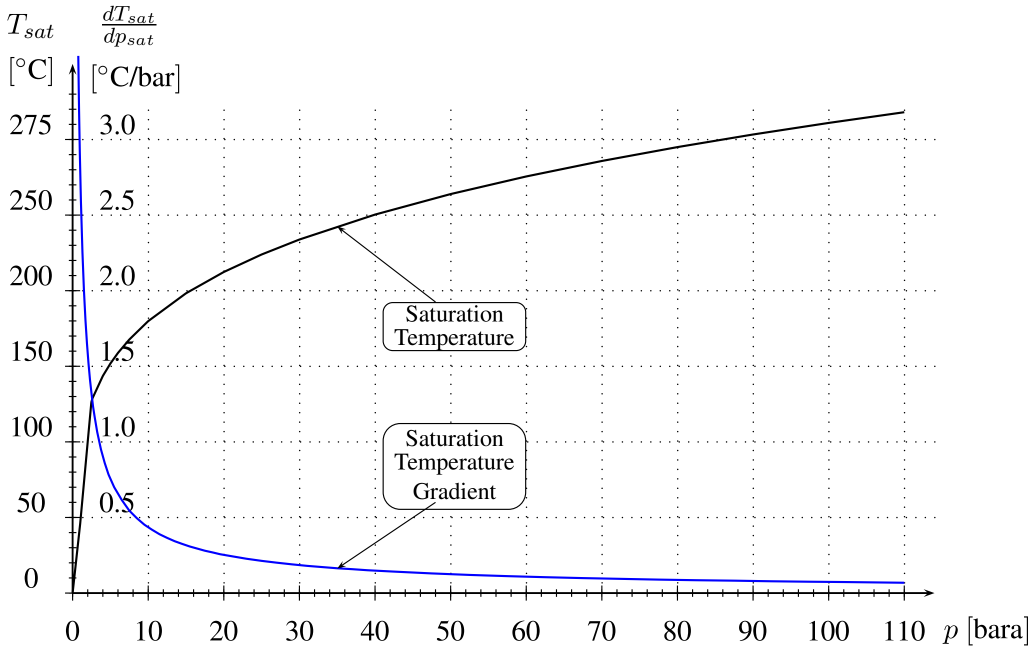

Figure 7: Saturation temperature and temperature gradient versus pressure for water/steam.

fluctuate to meet the specified steam mass flow. As mentioned the drum will experience saturation conditions, i.e. $(\frac{dT}{dt}) = (\frac{dT_{sat}}{dt}) = (\frac{dT_{sat}}{dp} \cdot \frac{dp}{dt})$ where $\frac{dT_{sat}}{dp}$ is a physical property and $\frac{dp}{dt}$ is determined by the operation of the plant. As $T_{sat} = f(p_{sat})$, the temperature gradient in the evaporator will be a function of the pressure gradient. The gradient of the saturation temperature with respect to pressure (i.e. $\frac{dT_{sat}}{dp}$) is much larger at low pressure than at higher pressure (see figure 7), i.e. the allowable pressure gradient for the boiler during low pressure operation will be lower than during operation with higher pressure.

6 CONCLUSION

In this paper a model for boiler heating surfaces and evaporator circuits has been given. The simulations have been verified at a full scale test plant. This serves as a basis for the Ph.D. project being written by the author, *Optimization of boilers with respect to dynamic performance*. The results from the dynamic model are being applied as constraints for an optimization of the boiler design with respect to dynamic performance.
The simulation models combined with the optimization model will be applied for verification during the remaining part of the Ph.D. project (*optimization of boilers*).

7 PERSPECTIVES

The Ph.D project will be finalized in the middle of 2004 and the following work is foreseen:

- Refinement of model
  - Full integration of flue gas and water/steam side
  - Further development of two-phase models
  - Modelling deviations from ideal (e.g. temperature distribution)
  - Improve models for sub-cooling
- Analyzing and verifying tests
- Optimization of design versus dynamic operation

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APPENDIX A
Nomeclature

In this appendix the applied symbols are explained.

Symbol	Content	Unit
A	Area	[m^2]
D	Diameter	[m]
M	Mass	[kg]
T	Temperature	[$degC/K$]
V	Volume	[m3]
h	Enthalpy	[kJ/kg]
$\dot{m}$	Mass flow	[kg/s]
l	Length	[m]
g	Acceleration of gravity (=9.816)	[m/s^2]
p	Pressure	[$bara$]
$\dot{q}$	Energy flow	[kJ/s]
u	Specific energy content	[kJ/kg]
v	Velocity	[m/s]
x	Quality	[$-$]
z	Length/height	[m]
α	Coefficient of heat transfer	[$W/m^2/K$]
λ	Coefficient of friction	[$-$]
ρ	Density	[kg/m^3]
φ	Angel of inclination (evaporator)	[rad]
$circ$	Circulation	[$-$]
ev	Evaporator	[$-$]
fg	Flue Gas	[$-$]

APPENDIX B
State of the art - Modelling and Simulation

During the years boilers have been the main subject for several modelling and simulation projects. In general the development of digital computers has been a necessary pre-condition of the boiler modelling and simulation. But even before the computers were developed to an acceptable level, dynamic models for boiler performance were formulated, and different simplification were made to be able to solve the equation systems.

Several authors have prepared summaries of the development within boiler modelling and simulation. Among the more comprehensive are [35] and [29]. [54] is a new reference summarizing the modelling and simulation of boilers. The main references highlighted in [54] are the works carried out by prof. R. Doležal, IVD[7] and prof. W. Linzer and prof. K. Ponweiser, TU-Wien. In the summaries results of the work carried and the future challenges are summarized.

One of the classical references within dynamic boiler modelling is [42], where the governing equations are formulated and special attention is paid to the control of boilers. [33] is another classical reference, which also focusses on control of boilers. A relatively new, very interesting reference within boiler and energy utilization is [44], which also has a detailed chapter about dynamic modelling of boilers as an integrated part of an energy utilization plant.

[7] Institute of Process Engineering and Power Plant Technology. In German: Institut für Verfahrenstechnik und Dampfkesselwesen - University of Stuttgart.

An important era within boiler modelling and simulation started with prof. Dr.-Ing. R. Doležal, who from the sixties until the mid nineties together with a number of researchers and Ph.D. students carried out a tremendous amount of work within boiler modelling and simulation. Prof. Dr.-Ing. R. Doležal was born in Slovakia, and started his academic career at the Technical University of Prague. Afterwards prof. Dr.-Ing. R. Doležal came to Switzerland and later to Germany. He first joined Gebrüder Sulzer, Winthertur, Switzerland and afterwards returned to the academic world at the Technical University in Braunschweig (Institut für Wärme- und Brennstofftechnik). From 1978 until 1992 prof. Dr.-Ing. R. Doležal was the leader of IVD [32] and today (2003) he is still emeritus at the university.

By means of the *de-coupled regenerative model* (see: [22] and [43]), prof. Dr.-Ing. R. Doležal formulated a model, that still forms the basis of the modelling activities being carried out at the IVD. The work of prof. R. Doležal has been applied as a basis of several Ph.D. studies. In the seventies and eighties, the work focussed on preparing and extending the models and on modifying the regenerative model to simulate the true recuperative heat exchangers in the boilers. The activities within boiler modelling and simulation initiated by prof. Dr.-Ing. R. Doležal now forms the basis of research activities within coupling of the flue gas and water/steam side in boiler modelling. The modelling and simulation of the flue gas side is carried out by means of CFD, where especially activities within furnace incl. burner modelling are carried out. The comprehensive activities at IVD has always been supplemented by experimental verification of the simulation results. Prof. Dr.-Ing. R. Doležal's most impressing list of publications includes items as:

- control of boilers [5], [6] and [7].
- planning of boiler plants [8].
- time constants for once-through and natural circulation boilers [9], [6] and [10].
- flow phenomenons for boilers (especially two-phase flow) [11], [17] and [13].
- modelling of natural circulating boilers [6], [14], [13] and [25].
- start-up of boilers [26], [16], [17], [18] and [40].
- modelling of boilers by mean of the *de-coupled regenerative model* [15],[3], [20], [21], [22], [23] and [24].

The work initiated by prof. Dr.-Ing. R. Doležal has been continued by prof. Dr.-Ing. Klaus R. G. Hein and today several Ph.D. students are carrying out research within this and related areas at IVD.

One of the latest works from IVD is [56], where focus is on modelling and experimental work as a basis of economical optimization of operation of boilers.

At the Department of Mechanical Engineering, Energy Engineering, DTU[8] intensive research within boiler modelling and simulation has been carried out for many years. As an integrated part of this work special attention has been paid to development of numerical methods for solving the equation system. Program codes for solving the DAE systems, which typically is the result of dynamic boiler modelling has been developed [29] and [39], and several projects verifying the validity of the codes have been carried out [29]. The activities at DTU has had a broader view than the activities at IVD. Together with the activities within boiler technology, activities have been carried out in e.g. refrigeration technology, engine technology and solar collectors. Furthermore studies within the modelling process have been carried out at the institute [30] and [31].

TU-Braunschweig [51] has also been very active within boiler modelling and simulation. Apart from the modelling and simulation activities attention has been paid to optimization of the operation of boilers, a special technique: *evolutionary algorithm*[9] has been applied, see [36], [35] and [38].

[8]The Technical University of Denmark (in Danish: Danmarks tekniske Universitet), see [48]
[9]*Evolutionary algorithm* has originally been developed within the biological science.

At the Technical University of Wien [49] research work has been carried out within the area of modelling of natural circulating boilers, and the SIMPLER algorithm, which is a general programme for modelling heat affected pipe systems, e.g. boilers, has been developed [53] and [55].

A more practical approach to control of boilers is given in [27]. This reference does not give a very detailed theoretical background, but is very useful for the practical oriented engineer.

A popular topic for optimization is the optimization of operation of plants with complex configurations e.g. plants with more boilers, steam turbine, gas turbines etc. As the different elements of the total plant have different investment and operation costs, the optimization of the operation of the plants to fulfil the externally given requirements (*constraints*) with respect to heat and electricity is extremely important. During the years more and more complex constraints (i.e. externally conditions) have been and still are implemented in the models [41], [34] and [47].

Apart from the above mentioned research activities within boiler modelling and simulation the following interesting references[10] have been found:

- [2] is an interesting model for simulation of evaporator circuits, the model is based upon the work of Tyssøe (1981).
- [28] describes the modelling and simulation of a complete power plant boiler. The author uses MATLAB for the simulations.

From the references found by the author, there seems to be the following main areas:

- activities within the modelling area.
- activities with focus on procedures and algorithms for solving the equation systems.
- activities with focus on optimizing operation of plants with complex *supply/demand* configuration.

no references have been found within optimization of boiler design with respect to dynamic performance, where the optimization mainly is related to optimization of boiler design with respect to dynamic performance. The *objective-function* to be optimized could in principle include all aspects (e.g. cost, footprint, emission and efficiency loss). Depending on the task to emphasize this term in the objective function will be weighted correspondingly.

[10] It has not been possible to assess to what extend these references are the result of *stand-alone* activities or a part of a research project.