Energy 36 (2011) 4633–4639

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Controller tuning of district heating networks using experiment design techniques

László Dobos, János Abonyi*

Department of Process Engineering, University of Pannonia, P.O. Box 158, H-8201 Veszprém, Hungary

ARTICLE INFO

Article history:
Received 24 November 2010
Received in revised form
7 April 2011
Accepted 8 April 2011
Available online 6 May 2011

Keywords:
Model predictive control
District heating network
Controller tuning
Experiment design

ABSTRACT

There are various governmental policies aimed at reducing the dependence on fossil fuels for space heating and the reduction in its associated emission of greenhouse gases. DHNs (District heating networks) could provide an efficient method for house and space heating by utilizing residual industrial waste heat. In such systems, heat is produced and/or thermally upgraded in a central plant and then distributed to the end users through a pipeline network. The control strategies of these networks are rather difficult thanks to the non-linearity of the system and the strong interconnection between the controlled variables. That is why a NMPC (non-linear model predictive controller) could be applied to be able to fulfill the heat demand of the consumers. The main objective of this paper is to propose a tuning method for the applied NMPC to fulfill the control goal as soon as possible. The performance of the controller is characterized by an economic cost function based on pre-defined operation ranges. A methodology from the field of experiment design is applied to tune the model predictive controller to reach the best performance. The efficiency of the proposed methodology is proven throughout a case study of a simulated NMPC controlled DHN.

1. Introduction

District heating was promoted in Europe in the 1950s. Nowadays EU-CHP Directive could assure the legal framework for applying district heating for member states of the European Union. District heating network is implemented to utilize the heat generated by the combustion of city waste or industrial waste heat. Thanks to the efficiency and environmental friendly characteristics, the role of the district heating is still increasing [1]. The main advantages of district heating systems are the following:

1. Energy efficiency thanks to the simultaneous generation of heat and electricity in CHPs (combined heat and power plants).
2. Environment friendly by implementing renewable energy sources and utilizing industrial waste heat.

Several variations exist for DHNs: in Ref. [2] the DHN includes several consumers located in different areas, but there is no energy storage and just one heat production unit. In Ref. [3], a storage tank is added to the network. In Ref. [4], a storage tank is also considered, but there is no thermal energy supply network. In some cases not just the local DHNs should be analyzed but the whole national DHN system, to investigate the sensitivity of the network, e.g. policy or even fuel price changes [5].

Modern optimal control and operation of a thermal plant and district heating network shall be a great project, especially if environmental aspects taken into consideration [6] and [7]. To reach this goal a proper and detailed description of the process is clearly needed like in Refs. [8] and [9]. Optimal operation means to meet the consumers' and environmental requirements and at the same time fulfill the restrictions to make the operation of the plant safe. Optimal control strategies meet these restrictions and at the same time minimize the operational costs or the environmental effects like in Ref. [10]. MPC (Model predictive control) methods are highly applicable for these purposes since the formulation of the objective function might imply every aspect. As MPCs require proper process model, the whole network has to be modeled.

The models of a DHN in the literature can be a physical description of the heat and mass transfer in the network, like Refs. [11] and [12], and utilize node method like in Ref. [13]. There can be another approach, based on a statistical description of the transfer function from the supply point to the critical point considered. The forecast methodology proposed in Refs. [14] and [15] is to set an ensemble of Auto-Regressive Moving Average with Exogenous input (ARMAX) models with different fixed time delays, and to switch between models depending on some estimated current

---

* Corresponding author. Tel.: +36 88 622793.
E-mail address: abonyij@fmt.uni-pannon.hu (J. Abonyi).

0360-5442/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2011.04.014

Nomenclature

α	tuning parameters of MPC
β	tuning parameters of MPC
$\Delta\mathbf{u}$	change in manipulated variables
γ	tuning parameters of MPC
λ	extension or contraction coefficient
ρ	density of the heat transfer fluid (kg/m^3)
$\mathbf{u}$	manipulated variables
$\mathbf{w}$	setpoint signals
$\mathbf{x}_m$	parameter vector of the simplex with the worst value of objective function
$\mathbf{y}$	controlled signals
ξ	mechanical loss coefficient
A	area for heat transfer in a cell (m^2)
c	value of control horizon
c_p	heat capacity of the heat transfer fluid (kJ/kgK)
E	length of modeling error vector
K	constant for trigger of IMC
L	length of the pipe (m)
M	number of optimized variables in simplex method
m	mass flow in the pipe (kg/s)
ME	modeling error vector
N	number of cells in the heat production unit
N_o	number of consumers
p	value of prediction horizon
P_i^{on}	income when the consumed heat in the ith consumer is inside the specification limits
Q	transferred heat in the heat production unit (kW)
Q_i^{on}	indicator in fulfilling the specification limits
R	radius of the pipe (m)
T	temperature in the pipe (K)
T_0	ambient temperature (K)
$T_c(i)$	temperature on the cold side in the ith cell (K)
$T_h(i)$	temperature on the hot side in the i^{th} cell (K)
T_{in}	inlet temperature in the pipe (K)
U	heat transfer coefficient (kJ/m^{2}K)
v	velocity of the fluid in the pipe (m/s)
V_c	the volume of a cell on the cold side of the heat exchanger
V_h	the volume of a cell on the hot side of the heat exchanger (m^3)

time. In Ref. [16] the gray-box modeling approach combines physical knowledge with data-based, statistical modeling. Physical knowledge provides the main structure and statistical modeling provides details on structure and the actual coefficients/estimates. This is advantageous since the physical knowledge reduces the model-space which must be searched, whereby the validity of the statistical methods is better preserved.

The aim of this work is to reduce the transition time in a non-linear model predictive controlled DHN presented in Ref. [17] by tuning the parameters of the non-linear MPC. The efficiency of the controller is measured by a cost function considering the limits of desired operation regime. To maximize this cost function the simplex method is applied, which is a well-known method in field of experiment design. This optimization method is able to handle mixed-integer optimization problems, which is needed because of the integer values of prediction and control horizon. Since there are periodic characteristics of heat demand, the proposed methodology can be easily inserted into an iterative learning control scheme [18].

The paper is organized as follows: in Section 2 the topology of the applied DHN will be introduced. In the second part of Section 2 the applied MPC solution and the tuning method are introduced and then in Section 3 the control and optimization results will be examined.

2. Modeling and control approach of a DHN

2.1. The applied topology and modeling approach

In this section the topology of the examined DHN is presented. The topology depicted in Fig. 1 is chosen to represent the main characteristics of a DHN. The network contains two heat production units, three consumers, two pumps and a valve. The production unit, called Producer 1, is the base load boiler, which may represent e.g. a waste incineration plant. The other production unit, called Producer 2, is the peak load boiler station, which has to satisfy the increased heat demand in the network, especially in case of Consumer 3. HX1 and HX2 heat exchangers are for transfer the produced heat from the primary circles to the secondary circle, which distributes the heat to the consumers directly.

The model of this network is developed using the method of Ref. [11], which applies the physical description of the heat and mass transfer in the network. Structural approach is used to obtain a convenient global model: considering the complexity of the system, local models of the components of the network are established and then brought together.

2.1.1. Heat exchangers

In order to get the proper dynamic behavior of the heat exchangers an approach using a cell model with ordinary differential equations was chosen [10]. The heat exchanger was divided into perfectly and instantly mixed tanks, each featuring a hot side and a cold side element (Fig. 2). As the number of cells increases the logarithmic mean temperature difference of the heat exchanger is approximated more accurately. It is assumed that each cell is perfectly homogenous, and no back-mixing occurred. Also, the

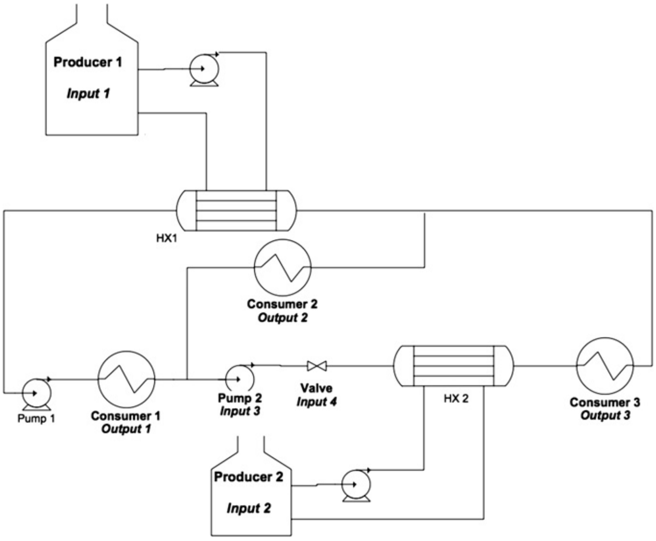

Fig. 1. Topology of the examined district heating network.