10th International Symposium on District Heating and Cooling

September 3-5, 2006

Tuesday, 5 September 2006

Sektion 6 b

Substations and user behaviour

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Dynamic performance of district heating system in Madumvej, Denmark

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Abstract

The Madumvej district heating system (Roedovre, Denmark) was simulated for two days with an emphasis on assessing its dynamic performance. Two approaches were used in the simulations, namely: i) the DHSIM simulation program developed at the Technical University of Denmark and at Risoe National Laboratory (Denmark) using the node method, and ii) the commercial software TERMIS. The simulation results were compared with actual system measurements, which were collected from a heat source and house stations at 6-minutes intervals. From this comparison, it could be concluded that the prediction of temperature values deviates significantly from the measured values in two extreme cases: i) during relatively large and sudden temperature changes at the heat source and ii) during periods with low velocities. Based on the analysis of the temperature wave propagation throughout the network, it was noted that the temperature wave spread unevenly at different locations in the network. The reason for this was the significant changes in velocity at some consumers, occurring at the moment of temperature wave disappearance.

Keywords: District heating; Dynamic temperature simulation

1 Introduction

The dynamic operation of district heating systems occurs due to heat load variations at consumer stations and due to changing supply temperature from a heat source, which is often more pronounced during high demand periods. District heating system performance prediction is useful for short term forecasting and is used when developing operational optimization models. The prediction models are usually based on many simplifications (e.g., one-dimensional idealized fluid flow) due to constraints on computational time, and therefore their validation is a highly important issue as well as the investigation of the factors affecting the quality of the model predictions.

However, validation of any predictive model requires measured data from an actual district heating system, where the data should preferably have small time discretization (compared to the rate of changes in a system) and be available for all consumers. In the presented work, this validation was possible through using data from Madumvej district heating system, which were recorded at a relatively short time interval, i.e., every 6 minutes. These measurements were collected from the house stations and a heat source by the Supervision, Control and Data Acquisition system

(SCADA). The Madumvej system was modelled by two approaches, namely the node method developed collectively at the Technical University of Denmark and Risoe National Laboratory (Denmark) [1], and the commercial software TERMIS [2]. The validation of the approaches was performed by comparing the modelling results with measured data for the return temperature at a heat source and the consumers supply temperatures.

Based on the comparison of modelled and measured data, situations were identified where the discrepancies between the predicted and measured temperatures were pronounced. Furthermore, we identified the factors that affected the spreading of a temperature wave and analyzed the tendencies that exist in temperature wave propagation throughout the network.

2 District Heating System and measured data

The Madumvej district heating subsystem serves 14 consumers and provides approximately 3 MW of total heat loads (Fig. 1). The subsystem is part of larger district heating system and connected to it through a heat exchanger, which in the model was treated as a heat source.

The Madumvej distribution network is shown in Fig. 1 and is built up of pre-insulated pipes with a total length of 2.71 km. The pipe diameter ranges from 40 mm to 200 mm.

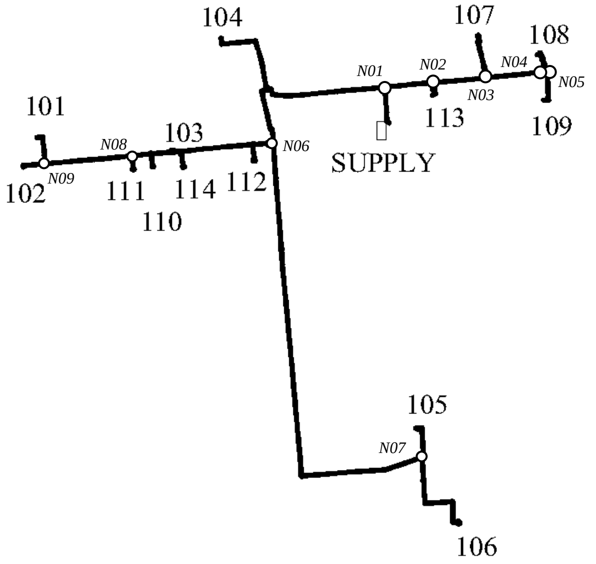

Fig. 1: Distribution network

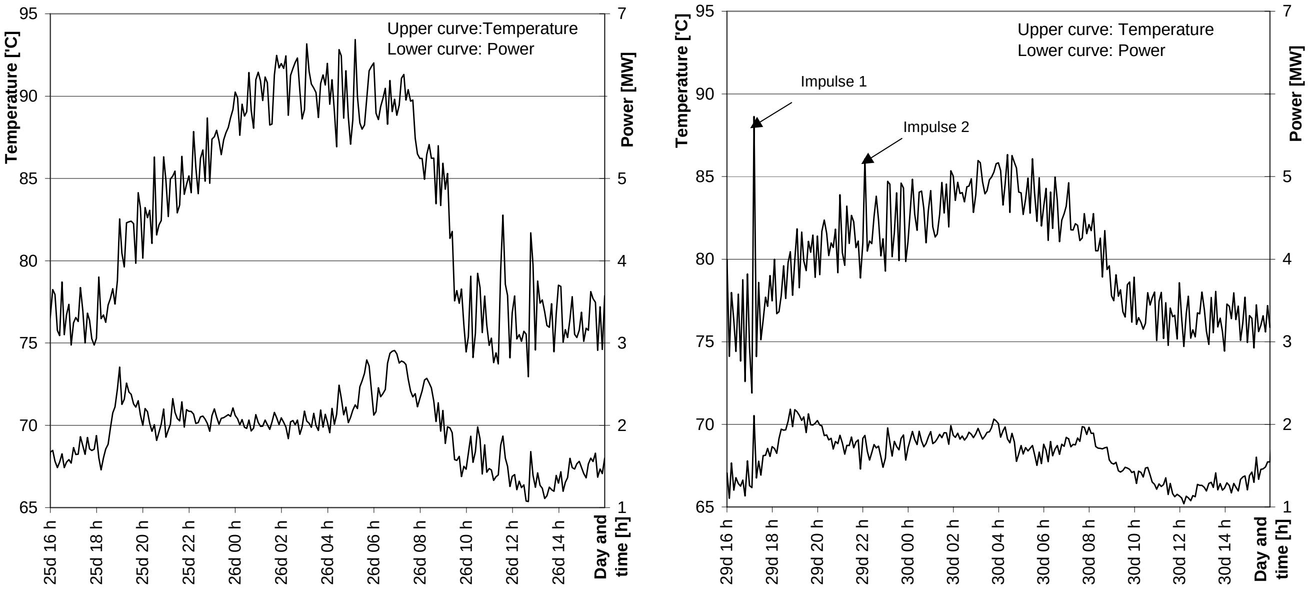

Fig. 2: Supplied power and temperature

Consumers are identified with numbers and are shown in Fig. 1. They are connected to the network through heat exchangers and are equipped with a local control system, which causes the variation in flow rate. The data that are used in the presented study contained measurements at the primary side of the consumer's installations. They include measurements of power, supply and return temperatures, which were collected at 6-minutes intervals. The measurements of the heat and temperature supplied to the subsystem were collected by the Supervision, Control and Data Acquisition system (SCADA). These measurements are presented in Fig. 2 for a time span considered in the modelling: 25-26 March, 2003 and 29-30 March, 2003.

3 Modelling consideration

In this study, a simulation programme called DHSIM was used. It has been developed at the Technical University of Denmark and Risoe National Laboratory. This program has previously been used in investigations by Palsson et al. [1] and Bøhm et al. [3], and is based on the so-called node model for estimation of temperature dynamics in pipelines ([4], [5]). The commercial software TERMIS [2] has also been used in the study for comparison purposes.

Both models are based on the quasi-dynamic approach, where the temperature is estimated dynamically while the flow and pressure are calculated on the basis of a static flow model. The fluid pipe flow is assumed to be one-dimensional and considered as an idealized flow. The temperature profile under such conditions is influenced by flow velocity and heat accumulation in the pipes, while the impact of the turbulent fluctuations and the secondary flow appearance are neglected.

The input data for the modelling are the measured supply temperatures at the heat source and data measured at the primary side of consumers installations, such as heat loads and cooling (i.e., difference between the supply and return temperatures). When considering the modelling conditions, the time step length plays an important role, since it defines the time discretization scale. This variable was set to 6 minutes for both approaches as it corresponded to the measured data resolution.

4 Simulations results

The simulation results obtained by the two approaches (node method and TERMIS) are presented in this section. They are compared to measurements for two one-day periods, i.e., 25-26 March and 29-30 March in the year 2003.

4.1 Comparison between two modelling approaches and prediction quality

Three parameters are introduced to describe the comparison between predicted and measured temperature values in a systematic way. First parameter, called the average error, is estimated by finding the difference between the predicted and measured values at each time step, and then averaging them over the simulation period. This parameter measured the quality of the heat loss estimation. The second parameter describes the standard deviation of this error, which is a measure of how accurate the time delay between a heat source and consumers is evaluated. The third parameter represents the average error relative to the temperature drop due to heat losses in a network (which are also averaged over the simulation period) (see eq. 1). The reason for introducing the last parameter is to eliminate the inaccuracies in estimation of heat losses, which are pronounced for long pipelines and low velocities. Even a very good simulation model will give large errors for long pipes with large heat losses and time delays. The relative error (found by dividing the error by the average temperature decrease along the pipe) will represent the quality of the simulation in a better way. Value of the relative error equal to unity signifies that the error in temperature estimation (called average error here) occurs solely due to inaccuracies in estimation of the heat losses, i.e., the difference between modelled and real heat losses.

The relative error in temperature prediction at consumers was estimated from the following equation: $K = \{(T_p - T_c)_s - (T_p - T_c)_m\}/(T_p - T_c)_m$ (1)

where T_p – the temperature at a heat source, and T_c – the temperature at a consumer. Subscripts $_s$ and $_m$ denote simulated and measured values, respectively. In equation (1), we assume that $(T_p)_s=(T_p)_m$, since the measured values at a heat source are used as the input data in the modelling approaches.

The above-mentioned parameters are presented in Table 1 for supply temperature prediction at all consumers. A negative value of the average error indicates that the temperature is under-predicted and vice versa.

Table 1: Average error, its standard deviation and relative error for predicted supply temperature at consumers for time period 25-26 March.

Consu-mers No	Node method		TERMIS	
	Aver. error (standard deviation) [^{o}C]	Relative error [-]	Aver. error (standard deviation) [^{o}C]	Relative error [-]
101	0.29 (1.20)	0.15	0.2 (1.41)	0.11
102	0.86 (1.19)	0.35	0.79 (1.37)	0.32
103	0.53 (1.07)	0.24	0.21 (1.15)	0.19
104	0.01 (1.05)	0.001	0.03 (1.29)	0.03
105	-0.02 (1.0)	-0.02	-0.15 (1.22)	-0.09
106	0.88 (0.89)	0.28	0.73 (1.16)	0.24
107	0.02 (1.10)	0.02	-0.03 (1.16)	-0.03
108	-0.03 (1.17)	-0.04	-0.07 (1.23)	-0.10
109	0.52 (0.89)	0.29	0.44 (1.09)	0.24
110	0.63 (1.11)	0.35	0.58 (1.16)	0.32
111	0.82 (0.99)	0.29	0.72 (1.06)	0.26
112	0.48 (0.94)	0.34	0.45 (0.99)	0.32
113	0.94 (1.01)	0.45	0.03 (1.8)	0.01
114	2.46 (1.14)	0.52	2.41 (1.15)	0.51

Table 2: Average error, its standard deviation and relative error for predicted supply temperature at consumers for time period 29-30 March.

Consu-mers No	Node method		TERMIS	
	Aver. error (standard deviation), [^{o}C]	Relative error [-]	Aver. error (standard deviation) [^{o}C]	Relative error [-]
101	-0.06 (1.29)	-0.04	-0.46 (1.8)	-0.3
102	0.46 (1.25)	0.23	0.08 (1.76)	0.04
103	-0.09 (1.2)	-0.12	-0.46 (1.66)	-0.6
104	0.02 (1.09)	0.02	-0.35 (1.52)	-0.3
105	-0.41 (1.22)	-0.33	-0.83 (1.70)	-0.6
106	0.83 (0.79)	0.27	0.41 (1.19)	0.13
107	0.06 (1.07)	0.05	-0.33 (1.52)	-0.27
108	-0.4 (1.39)	-0.9	-0.79 (1.82)	-1.89
109	0.52 (0.89)	0.28	0.13 (1.33)	0.02
110	0.63 (0.98)	0.35	0.26 (1.35)	0.26
111	0.46 (1.14)	0.18	0.02 (1.72)	0.01
112	0.52 (1.03)	0.31	0.18 (1.60)	0.11
113	0.54 (1.32)	0.35	-0.94 (1.79)	-0.16
114	3.02 (1.16)	0.52	2.6 (2.02)	0.45

From Tables 1 and 2 it can be seen that an average error is considerably larger for industrial consumer 114. The reason for this is low velocity regime in the consumer intake pipe, which causes high heat losses compared to other pipes. The average velocity in this pipe was in the order of 0.02-0.04 m/s combined with velocity drop to as low as 0.001-0.01 m/s (see Fig. 3), which occurred due to the small heat load for the simulated days. The flow regime in the consumer intake pipe is very important for such extreme conditions, because other consumers, for example consumers 112 and 103, that are connected to the same branch together with consumer 114 (branch N06-N08-N09 in Fig. 1), have smaller average error, i.e., less than 1^{o}C. Thus, it is more likely that the low averages velocities, in the order of 0.04 m/s and less, combined with velocity drop to values very close to 0 will result in large deviations from the measurements.

The relative error is highest for consumer 114 during time period 25-26 March for both modelling approaches (see Table 1). However, for the other time period 29-30 March, the difference between the approaches is not uniform and TERMIS produced somewhat larger relative errors (see Table 2).

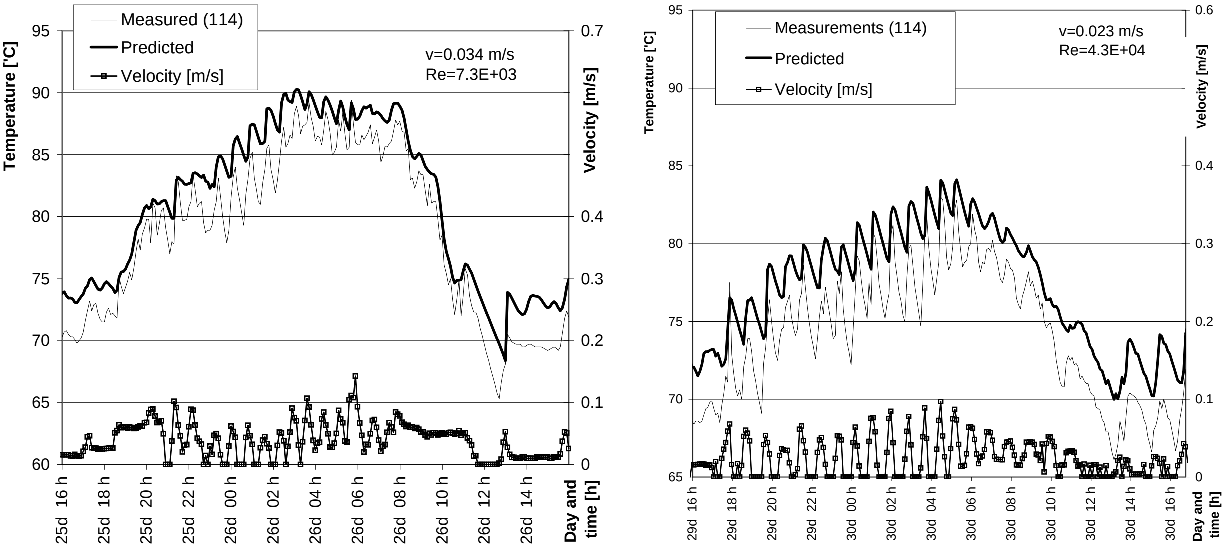

Fig.3 Temperature and velocity for consumer 114 for March 2003, 25-26 d.(picture on the left) and 29-30 d. (picture on the right)

Concerning the return temperature prediction at a heat source the average error constituted 0.09 ^{o}C for the node method and -0.09 ^{o}C for the TERMIS software. The standard deviation of this error was 0.29 ^{o}C and 0.61 ^{o}C, respectively.

4.2 Temperature wave spreading time

In this section, we analyze the spreading time of a temperature wave, which occurs every day from approximately 18:00 to 11:00 o'clock. The wave spreading time is defined as the time period during which a temperature wave starts and ends at a given spatial location, for example at a consumer substation. This spreading time was 16 hours at the heat source (for 25 and 26, March) and it remained the same for the bulk of consumers. The exception is for consumers 105 and 106, which have larger spreading times of approximately half an hour (Figs. 4). At those consumers, the starting time of temperature wave is 19:00 and ending time is 11:36, resulting in a spreading time equal to 16h. 36 min. For a consumer with shorter wave spreading time, for example consumer 101, the wave starting time was 18:54 and ending time 10:48, which constitutes approximately 16 hours. This tendency of two consumers (105 and 106) to have longer spreading time than others is observed for the entire analysed period. For example, on another day (29-30 March), the spreading time at those consumers was 18 hours, which is one hour longer than that for the majority of consumers, i.e., 17 hours.

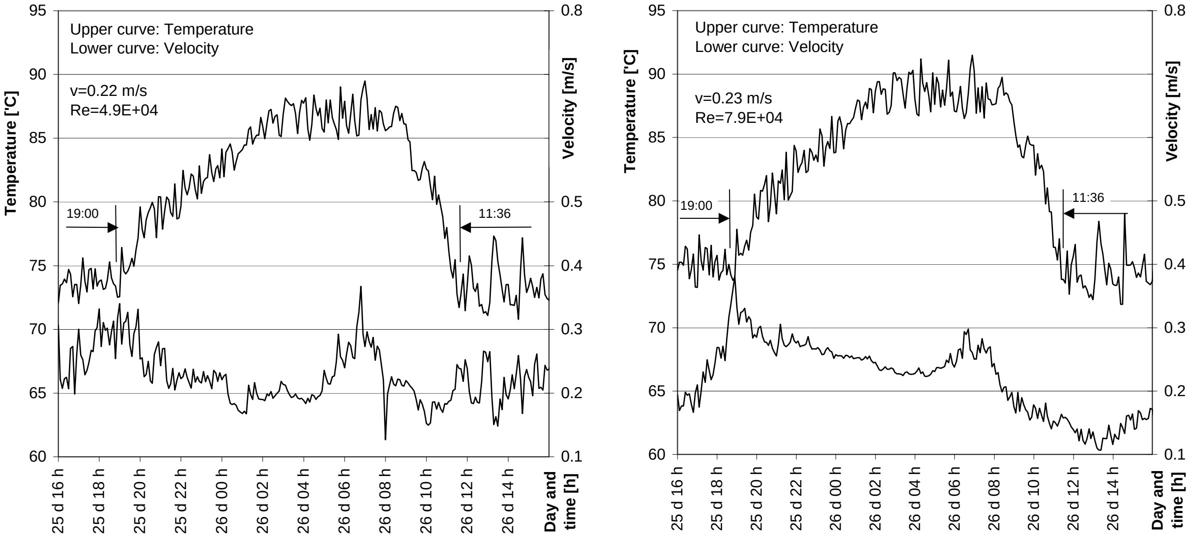

Fig. 4: Temperature and velocity for consumers 106 (left picture) and 105 (right picture) for 25-26 March, 2003.

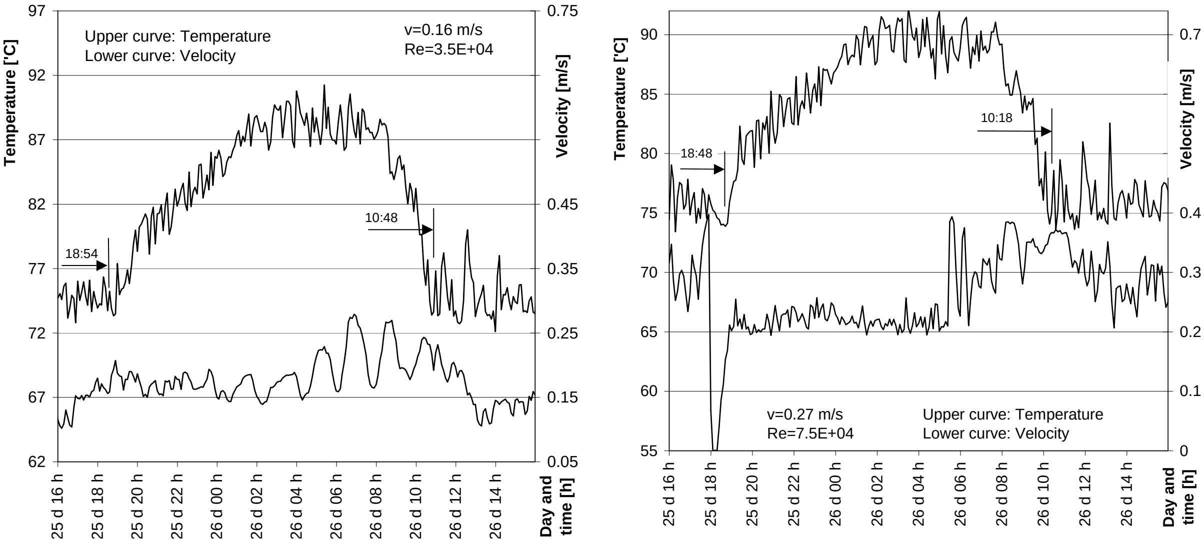

Fig. 5: Temperature and velocity for consumers 101 (left picture) and 104 (right picture) for 25-26 March, 2003.

The possible reasons for the uneven wave spreading time at different points in the network could generally be attributed to the network geometry and the fluid flow conditions. Network geometry, such as fittings, elbows and fork connections, can influence a temperature wave by creating pronounced secondary flow. This effect is magnified when a number of fittings are concentrated over a short distance, resulting in increased rates of thermal diffusion (i.e., diffusion of heat due to turbulent fluctuations). The flow conditions include changes in the overall and local velocities. If local velocity fluctuations have large amplitude and occur periodically, the temperature wave can be affected due to possible changes in the overall turbulent intensity, which directly induces rates of heat diffusion. In view of these remarks, the flow conditions during the wave occurrence were detailed for the pipelines before consumers 105 and 106, and consumer 101. The magnitude of velocity fluctuations was somewhat greater in the pipelines preceding consumer 101, which is shown in Fig. 5 (left picture) for pipeline N08-N09. The significant decrease in overall velocity level is noticeable in pipelines located before consumers 105 and 106 at 7:42, which is presented in Fig. 6 for pipeline N06-N07. The location of these pipelines in the network is indicated in Fig. 1.

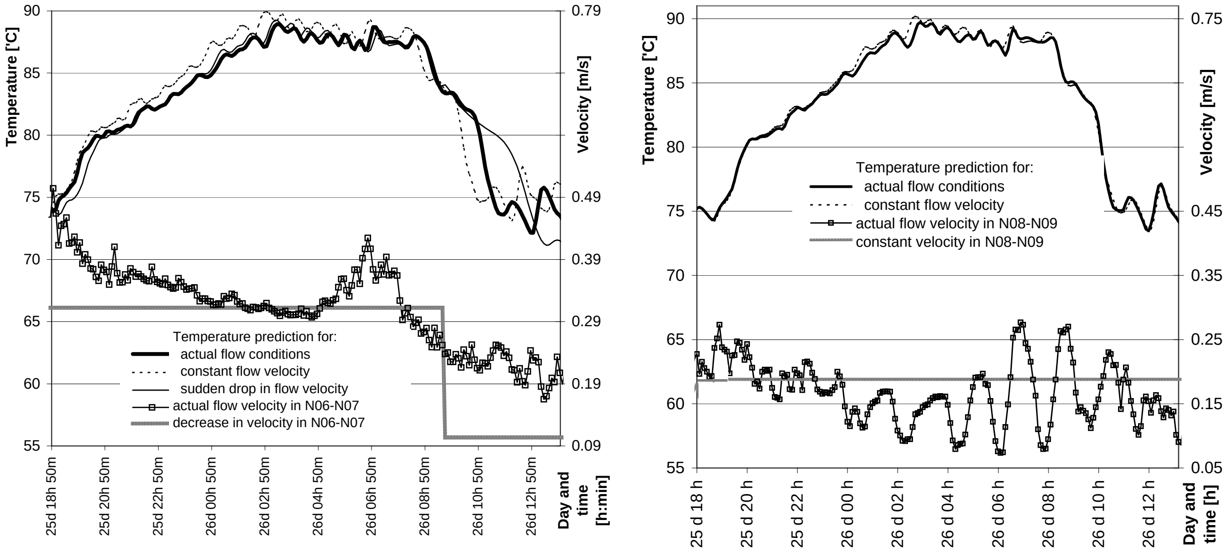

Fig. 6: Temperature predictions for consumers 106 and 101 for different fluid flow conditions: i) constant flow velocity, ii) decrease in a velocity level (only for consumer 106) iii) actual flow conditions.

In order to investigate the reason for large wave spreading time, the following modelling scenarios were considered for two pairs of consumers 101, 102 and 105 106: i) a constant velocity for the consumers (one pair at a time); ii) a flow regime with a rapid decrease in a velocity level, which occurs at 9:36 (Fig. 6) during the wave disappearance period (only for consumers 105 and 106).

The results from these scenario simulations are presented in Fig. 6 for consumers 106 and 101, (one consumer for each pair). It can be seen that for the consumer 101 (Fig. 6 right picture), the modelling of the case (i), with constant velocity, does not change the temperature wave at all compared to the actual flow conditions. This implies that the velocity fluctuations in preceding pipelines (shown in Fig. 6) have little effect on the temperature wave. However, for consumer 106, the modelling of this case has resulted in a smaller wave spreading time compared to actual conditions. This suggests that the decrease in flow velocity found in measured data (at 07:42, Fig. 6 left picture) was large enough to influence the temperature wave. This was confirmed by results from modelling the case with the enlarged drop in flow velocity, which demonstrated an even more increased wave spreading time (compared with the actual flow conditions). Thus, the reason for greater wave spreading time for consumer 106 is a rapid decrease in flow velocity level, which occurs at 7:42 during the wave disappearance period. The velocity declined by approximately 40% during two hours interval. The same tendency was observed for consumer 105, when modelling the above-mentioned flow conditions.

It can be concluded that large changes in overall velocity level (e.g., a velocity decrease of 40% produced over an two-hour interval), which take place during the temperature wave disappearance, influence the wave spreading time significantly.

The investigation of temperature wave behaviour as it propagates throughout the network is useful, as it could highlight the factors that affect it, which in turn, can be used when considering the different operational strategies.

4.3 Large changes in supply temperature

In this section, the propagation of steep changes in supply temperature and its prediction are detailed. We consider only the cases with moderate velocity fluctuations, thus excluding the effect large fluctuations might have on the temperature changes. These conditions were found in a part of the network supplying heat to four consumers: 108, 109, 107 and 113 (Fig. 1). Velocity fluctuation at those consumers can be seen in Figs. 7 and 8, along with average velocity and Reynolds numbers in the consumers' intake pipe. This information is also presented for pipelines prior to these consumers' intake pipes (Fig. 9). From Figs. 7-9 it can be seen that the local fluctuations of velocity are moderate, a maximum of 10-30% from average value, and the velocity level is fairly constant over the presented time period (from 16:00 on 29th March to 04:00 on 30th March). Such velocity fluctuations can in principal be approximated as periodical, which at relative amplitudes of 10-30% produce a small variation in local heat flux quantities. However, this has no measurable effect on the average heat transfer [6]. Consequently, it would be appropriate to conclude that velocity fluctuations of such kind would not affect the fluid temperature significantly.

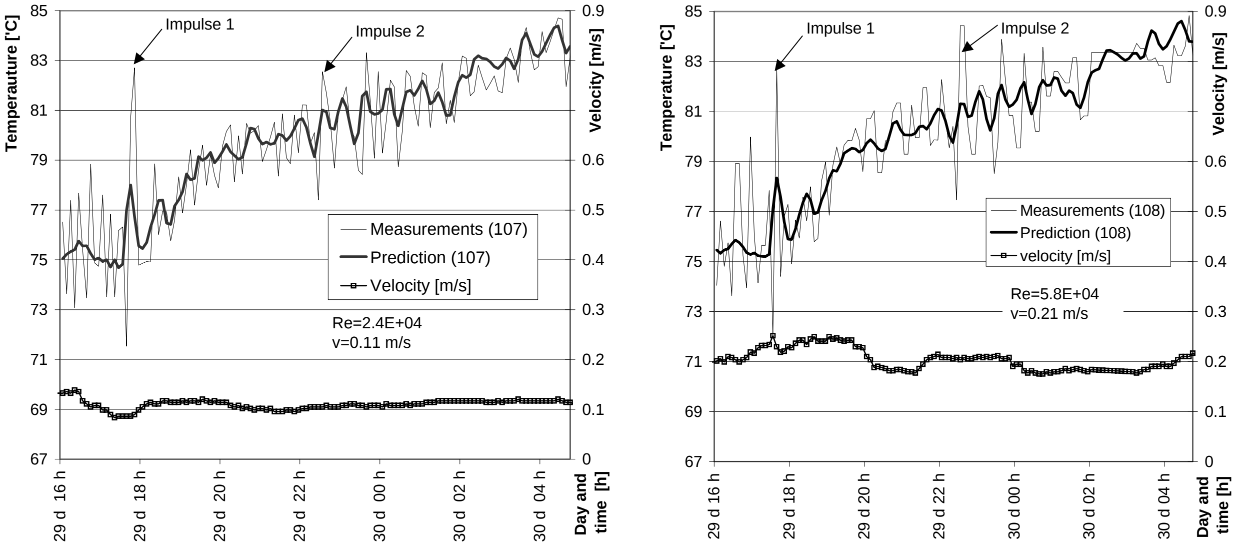

Fig. 7 Temperature and velocity for consumers 107 (picture on the left) and 108 (picture on the right) for 29-30 March, 2003.

It was found that the sudden and large temperature changes at the heat source resulted in inadequate prediction of temperature values at consumers' substations, whilst prediction of time moments of these changes correlates well with the measurements. Two impulse-like temperature changes, considerably larger than other changes, were observed at the heat source after 17 o'clock and 22 o'clock (Fig. 2, right picture). The first impulse, having a value of 16 °C between the lowest and highest impulse points, introduces a deviation between the predicted and measured temperatures higher than 4 °C. The second impulse (7.2 °C) produces a deviation between predicted and measured temperatures higher than 2 °C, while the typical value of maximum scattering between those values is found to be within 2 °C, when the temperature changes were smaller than the impulses. The prediction of the above-mentioned impulses is shown in Figs. 7-8 for consumers 108, 109, 107 and 113.

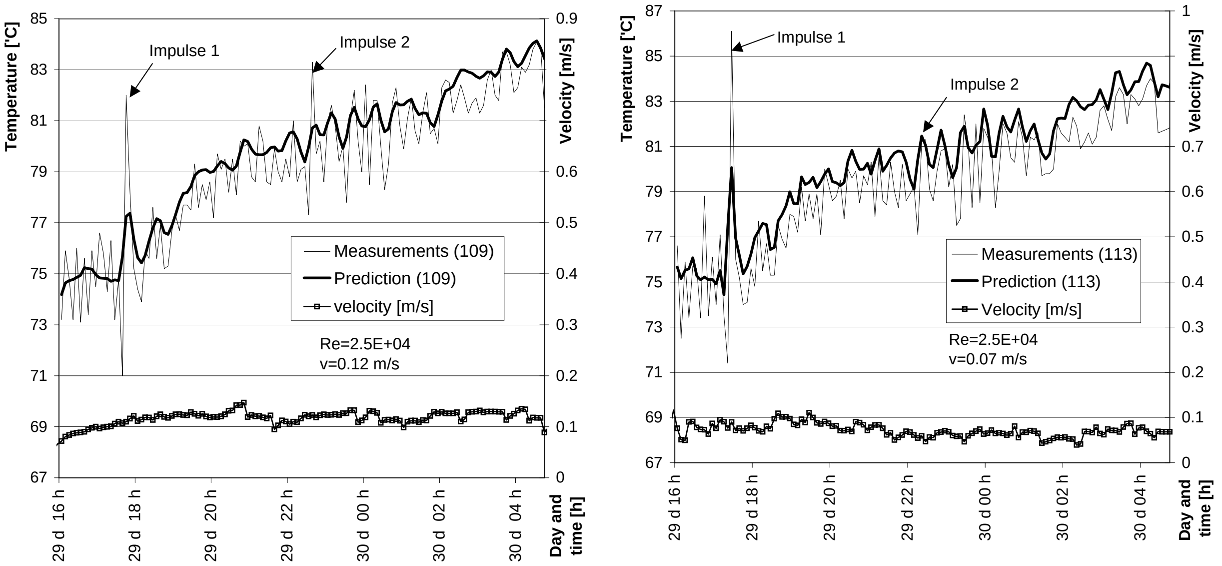

Fig. 8: Temperature and velocity for consumers 109 (picture on the left) and 113 (picture on the right) for 29-30 March, 2003.

Moreover, it was noted that large changes in the supply temperature are diminished by a greater magnitude after propagating throughout the network than initially small temperature changes in the supply temperature. When considering the two above-mentioned impulses, it can be observed that the first impulse (having a value of 16 ^{o}C between the lowest and highest impulse points) is diminished by up to 64% by the time it reaches the consumers. The values of this impulse were 14.7 ^{o}C, 11.2 ^{o}C, 11 ^{o}C and 10.5 ^{o}C at consumers 113, 107, 109 and 108, respectively (Figs. 7-8, impulse 1). The second impulse of 7.2 ^{o}C was diminished by up to 36%, when it reaches the consumers and hence consumers 113, 107 109 and 108 have values of 4.5 ^{o}C, 5.2 ^{o}C, 6.9 ^{o}C and 6 ^{o}C, respectively (Figs. 7-8, impulse 2).

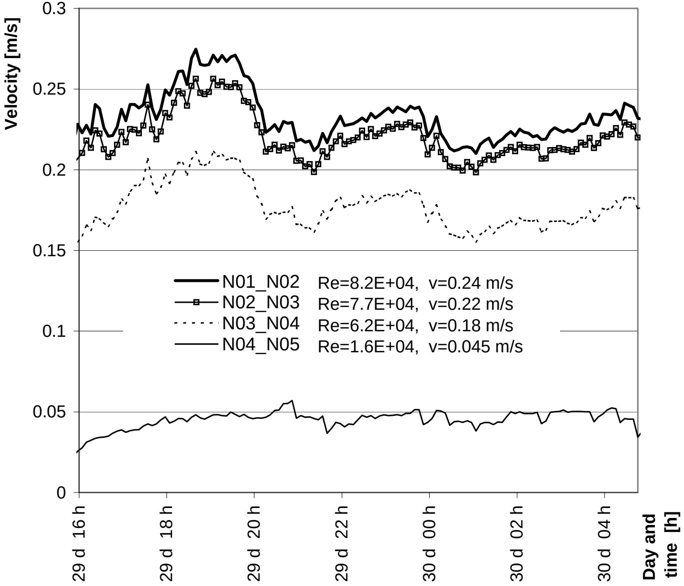

Fig. 9: Measured velocity in the pipelines preceding consumers 107, 108, 109, 113 for 29-30 March, 2003. The location of the pipelines is shown in Fig. 1.

Thus, it can be concluded that the magnitude of changes of the temperature impulse whilst travelling throughout the network is highly dependent on its initial value. The larger this value is, the more significant the magnitude of its changes is. Moreover, unfavourable conditions from the modelling viewpoint constitute situations where large initial temperature changes are present. It appears, that under such conditions, the prediction of temperature values is less reliable.

5 Concluding discussion

The Madumvej district heating system (Roedovre, Denmark) was modelled by two approaches, namely the DHSIM simulation program developed collectively at the Risoe National Laboratory and the Technical University of Denmark, and the commercial software TERMIS. The results of the modelling were compared with measured data. Based on this comparison, it was found that both models represented the time delay between a heat source and consumers with reasonable degree of accuracy, i.e., measured and predicted time values match exactly or deviate within one time interval of 6 minutes. The prediction of temperature values, however, deviated significantly from the measured values in two extreme cases: i) relatively large and sudden temperature changes at the heat source (e.g., an impulse of 8-16^{o}C produced over approximately 20 minutes) and ii) low velocities (of the order of 0.04 m/s and less).

Additionally, the factors that can affect the temperature wave propagation throughout the network were examined. Such factors include, but not limited to, changes in the velocity level, its fluctuation magnitude and the consumers' location in relation to the heat source. It was found that the reason for uneven wave spreading at different locations in a network could be attributed to the large changes in overall velocity levels at some consumers (e.g., a velocity decrease of 40% produced over a two-hour interval), occurring at the moment of temperature wave disappearance. It was also noted that the magnitude of changes of a temperature impulse whilst travelling throughout the network is highly dependent on its initial value. The larger this value is, the more significant the magnitude of its changes is.

Acknowledgments

Authors are thankful to Jens Munk Pedersen and Steen Cloos, Rødovre DH Company (Rødovre kommune, Driftsafdelingen) for providing the data for the analysis. 7-Technologies is also gratefully acknowledged for providing the software TERMIS to be used in this work.

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