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NUMERICAL SIMULATION OF A DISTRICT HEATING SYSTEM WITH EMPHASES ON TRANSIENT TEMPERATURE BEHAVIOUR

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Abstract. Numerical simulation of a district heating system was performed with emphases on transient temperature behaviour. The distortion of transient temperature throughout a heating system network was simulated using modelling approach developed at the Technical University of Denmark (the so-called node method). The commercial software TERMIS has also been used in this work for comparison purposes. The main focus has been placed on an analysis of system behaviour and how it could be represented by modelling tools for pronounced thermal and hydraulic transient regimes, in particular, temperature waves combined with temperature fluctuations. For this purpose, a district heating system in Madumvej (Denmark) and its operational conditions were analyzed. The time-dependent consumer data and heat supply data from the district heating system in Madumvej (Denmark) were applied for modelling. The results obtained from modelling approaches were compared with measured data at consumers' substations.

Keywords: district heating; dynamic temperature simulation; dynamic consumer behaviour.

1. Introduction

The main advantage of district heating systems lies in providing an infrastructure for development of integrated energy supply technology, which offers a possibility for an efficient use of local surplus heat sources from industrial processes and low-grade heat sources, such as geothermal energy. It also provides a possibility for an environmental safe use of low-grade domestic fuels. Fuel supply reliability and flexibility is enhanced by using local fuels like biomass or waste. As systems grow more and more integrated, the use of complex operational strategies become a necessary part of efficient system performance. Developing these strategies present a challenge, not just because of variable demand of the end-users, but also due to the varied heat supply from different heat recourses. The different strategies are introduced, for example the start-up of recourses that are only used to cover peak demands (otherwise kept on the stand-by regime) and increase heat production in the specific time periods. The strategy that incorporates recourses of waste heat depends on character of industrial processes and varies the amount of supplied heat depending and demand, price and availability. As a result, the operation conditions are never stable and involve pronounced thermal and hydraulic transient regimes, in particular, temperature waves combined with temperature fluctuations. Due to variation in the amount of supplied heat, the use of complex operational strategies becomes a necessary part for efficient system performance, which can be implemented by modelling dynamic performance of district heating system. Prediction of operational regimes, including thermal and hydraulic regimes in district heating systems are required for short and long term forecasting, and for performing dynamic temperature control of district heating systems.

The performance of district heating systems has been previously investigated in (Larsen *et al.* 2002, Larsen *et al.* 2004) with a focus on the district heating modelling. Authors discussed the strategies to reduce computational time and proposed new methods to reduce the network size. A steady-state model for estimation hydraulic regimes in district heating systems has been developed in (Gabrielaitienė *et al.* (2002) and Stevanovic *et al.* (2007). Other models describe the simulation results concerned with transient behaviour of district heating systems, particularly the modelling of transient behaviour in a several branches of a pipe network has been presented in (Gabrielaitienė *at al.* 2003) and (Palsson *et al.* 1999). Modelling of a district heating system has been presented in (Larsen *et al.* 2004), where the information about time-dependent consumer behaviour is limited. In the above-mentioned work, the data for time-dependent heat consumption were only available for some of the consumers. For the remaining consumers, the averaged heat consumption was used. The unique aspect of this work is the application of time-dependent measured data available for all consumers in a district heating system, which enables to represent the realistic performance of the simulation model.

In this study two models have been employed, namely the node method developed at the Technical University of Denmark (Palsson 2000) and the commercial software TERMIS. In these models dynamic temperature simulations are based on idealized flow conditions, where changes in temperature profile are influenced by flow velocity and heat accumulation in the insulated district heating pipelines. Other methods, such as the element method (Gabrielaitienė *et al.* 2008) and the model developed in (Stevanovic *et al.* 2009) have not been applied because of their similarities to the chosen methods or because of their modelling limitations.

2. Numerical method and modelling consideration

Principles for modelling transient temperature behaviour In this work, a node method developed at the Technical University of Denmark and Risoe National Laboratory (Palsson *at al.* 1999 and Bohm *at al.* 2002). The commercial software TERMIS (TERMIS 2010) 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 the 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 pipe, while the impact of the turbulent fluctuation and the secondary flow appearance are neglected. Eq. 1 presents the basis for the estimation of temperature dynamics.

$$\frac{\partial}{\partial t}(A_f \rho_f c_{p_f} T_f) + \frac{\partial}{\partial x}(V \rho_f c_{p_f} T_f) + hA(T_f - T_p) = 0 \quad (1)$$

where T_f and T_s – temperature for fluid and surroundings, respectively; V – volume flow m^3/s; A_f – cross sectional area of the pipe (m^2); A – area of a pipe internal surface per unit (1m) length (m); ρ – density (kg/m^3); h – the heat transfer coefficient (W/m^{2}K); c_p – specific heat (J/kgK).

The node method The node method considers the pipe flow, consisting of two nodes, inlet and outlet, for which values of mass flow rate and temperature are assigned. The outlet temperature is estimated from the temperature at the inlet node by taking into account the flow time from one node to another and the changes in flow velocity (Fig 1). The obtained temperature is then corrected to account for effects of the pipe wall heat capacity and heat losses.

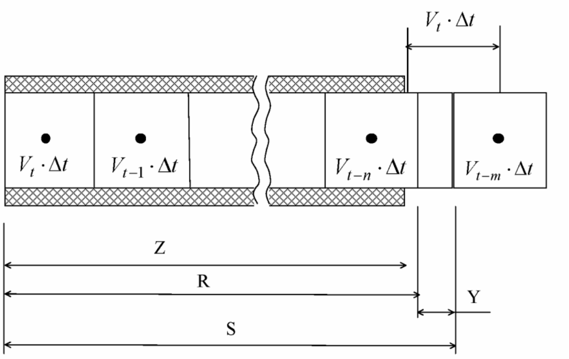

Fig 1. Principle of the node method in an insulated pipe, where *dt* – time step interval, V – volume flow

The following three steps can be distinguished in the node method procedure:

1. Temperature at the outlet node T_j at current time step t, denoted as $T_{j,t}$, is estimated from the following equation (see also Fig 1.):

$$T_{j,t} = \frac{(R - Z) \cdot T_{i,t-n} + Y + (V_t \cdot \Delta t - S + Z) \cdot T_{i,t-m}}{V_t \cdot \Delta t} \quad (2)$$

where: V_t – volume flow (m^3/s); t – current time step (s); Δt – time step interval (s); Z – total water volume in the pipe (m^3); $T_{i,t\ 1}$ – temperature at the inlet node at current time step t, and the superscripts n and m define the value of how many time steps should be subtracted from the current time step. The n indicates the number of time steps since the mass flow left the node, and is defined as the lowest integer number, which fulfils the following conditions:

$$\sum_{k=t-n}^{t} (V_k \cdot \Delta t) > Z;\ n \in [0, 1, 2, ...] \quad (3)$$

The integer m is defined as the lowest integer number, which fulfils the following conditions:

$$\sum_{k=t-m}^{t} (V_k \cdot \Delta t) > Z + V_t \cdot \Delta t;\ m \in [0, 1, 2, ...] \quad (4)$$

The variables Y, R and S are estimated from:

$$Y = \sum_{k=t-m+1}^{t-m-1} (V_k \cdot T_{i,k} \cdot \Delta t) \quad (5)$$

$$R = \sum_{k=t-n}^{t} (V_k \cdot \Delta t); \quad (6)$$

$$S = \sum_{k=t-m+1}^{t} (V_k \cdot \Delta t) \; if \; m > n \text{ and } S = R \, if \; m = n \qquad (7)$$

2. Accounting for the effect of pipe wall capacity ($T'_{j,t}$).

A heat balance gives:

$$C_p \left(\frac{T'_{j,t} + T_{j,t}}{2} - T_{p,t-1} \right) = V \cdot \rho_f \cdot c_{f_p} \cdot \Delta t \cdot \left(T_{j,t} - T'_{j,t} \right) (8)$$

where: $T_{p,\, t-1}$ – pipe wall temperature from previous time step, C_p – pipe heat capacity (J/K).

In the case of $V \cdot \rho_f \cdot c_{f_p} \cdot \Delta t = 0.5 \cdot C_p$, the assumption of $T'_{j,t} = T'_{j,t-1}$ is introduced to avoid the temperature, $T'_{j,t}$, becoming negative. When the temperature $T'_{j,t}$ is estimated, the pipe wall temperature $T_{p,t}$ is updated and then it is used in the next time step.

3. Accounting for the effect of heat losses to the surroundings ($T''_{j,t}$):

$$T''_{i,t} = (T'_{i,t} - T_{gr}) \cdot \exp\left(- \frac{L \cdot K}{V \cdot \rho_f \cdot c_{f_p}} \right) + T_{gr} \qquad (9)$$

where: K – overall heat transfer coefficient (W/m^{2}K), L – is the pipe length, T_{gr} – temperature of the surrounding soil. The volume flow (V) is based on an average velocity through the pipe (u), which is estimated from:

$$u = \frac{L}{\Delta t \cdot (n \; - 1 + e \;)} \qquad (10)$$

where the denominator denotes the mass transport time through the pipe (s).

The variable e is defined by the following equation:

$$e = \frac{S - R}{V_{t-n} \cdot \Delta t} + 3/2 \qquad (11)$$

The boundary condition is the temperature of surrounding ground. For the numerical solution, an in-house code, based on the finite difference method, was developed at the Technical University of Denmark. The accuracy of this code was examined as a function of the node distance and time step (Benonysson 1991, Palsson 2000).

TERMIS software Similarly to the previously described approach, the approach implemented in commercial software TERMIS (TERMIS 2010) is based on the quasi-dynamic assumption, 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, which is based on Eq. (1). The equation is solved in TERMIS, considering that the heat transfer coefficient (h) represents the overall heat transfer coefficient. In this case, the Tp (in eq. 1) describes the temperatures for surroundings, i.e., ambient air. The heat transfer coefficient is used as an input parameter, and is defined by a user.

Modelling consideration The difference between the models lies in the estimation of the heat transfer between the fluid and its surrounding. More particularly, the heat capacity of the metal pipe and heat accumulation in pipes is neglected in TERMIS software. In the node method, the overall heat transfer coefficient is based on the method of thermal resistances (Holman 1997) and the influence of two neighbouring pipes (the return and supply pipes) is accounted for. As this approach is not used in TERMIS, the heat transfer coefficient estimated by the node method was applied in the TERMIS software.

To ensure similar modelling conditions, the same time step length was used in both models, which together with pipelines discretization, determined the accuracy of the simulations. The discretization of pipelines was handled automatically and depended on the time step length.

The dynamic consumer behaviour was represented by the measured time-dependent heat load and by the measured time-dependent temperature difference between supply and return primary temperatures. The later described the cooling ability of a customer substation. The measured supply temperature at a heat source was used as model input value.

3. Numerical method and modelling consideration

In this work, Madumvej district heating subsystem is considered, because it has pronounced temperature dynamics in the supply temperature. A temperature wave was produced in heat production unit and local temperature fluctuations were depicted. Moreover, measured time-dependent data of inlet temperature and power were collected in heat source along with data for all consumers in subsystem. These two conditions enable a realistic representation of district heating system by a simulation model. It also enables to verify the simulations results by comparing the measured and simulated data.

A Madumvej subsystem serves 14 consumers, providing approximately 3 MW of total heat loads. It is connected to large district heating system through a heat exchanger. Consumers are also connected to the network through heat exchangers and are equipped with a local control system, which causes the variation in flow rate. The Madumvej distribution network is shown in Fig 2, which is constructed of pre-insulated pipes of a total length of 2.71 km and range in pipe diameters from 40 mm to 200 mm. More information about Madumvej district heating can be found in (Gabrielaitienė *et al.* 2006).

When performing a simulation of the district heating system, the heat exchanger which connects Madumvej subsystem to the rest of the system was treated as a heat source in the model. In this substation, the heat supplied to the subsystem was measured. Consumers (identified with numbers in Fig 2) were regarded as substations, serving a single building.

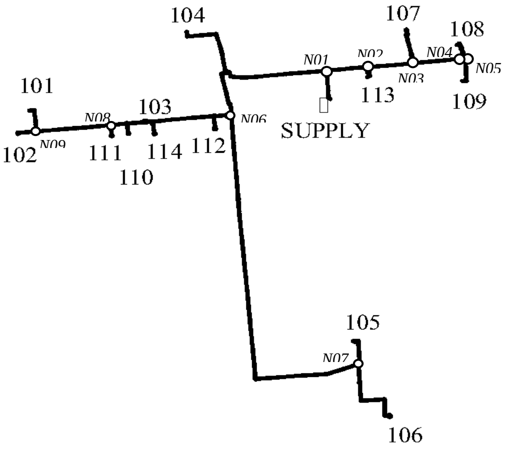

Fig 2. Distribution network of the Madumvej district heating system

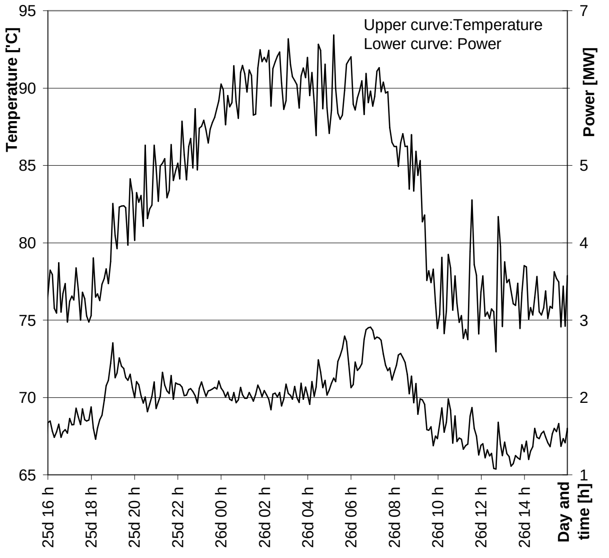

Fig 3. Supplied power and temperature for the first considered time period

The consumer data 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 temperatures supplied to the subsystem were collected by the Supervision, Control and Data Acquisition system (SCADA). Two time period were considered in this study, because in the first time periods the pronounced temperature wave was produced, while in a second time period the significant temperature fluctuations (regarded as a temperature impulse) were depicted.

These data are presented in Figs 3 and 4 for the first considered time period (25-26 March) and the second considered time period (29-30 March), respectively.

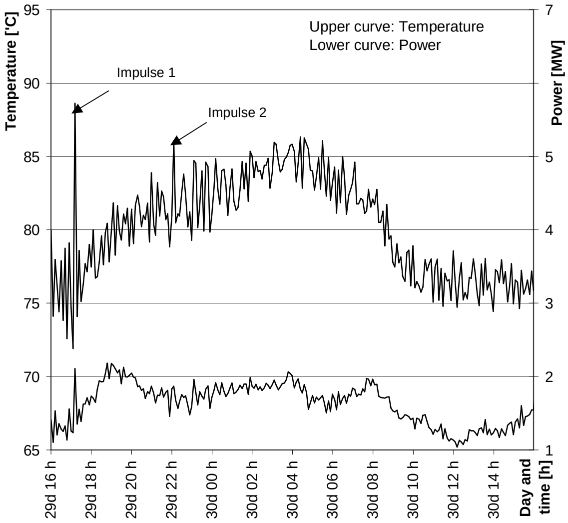

Fig 4. Supplied power and temperature for the second considered time period

4. Prediction quality for transient supply temperature

The difference in predictions obtained by the node method and TERMIS software is examined by comparing with time-dependent measured data. Two 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 - a relative error - represents the quality of the temperature value prediction. It was found by dividing the so-called average error (i.e., the difference between predicted and measured temperature values) by the measured temperature decrease along the pipe, which represents real heat losses in a given pipe (see eq. 11). If the relative error equal to unity it indicates 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:

$$\text{Error} = \frac{\left(T_p - T_c\right)_s - \left(T_p - T_c\right)_m}{\left(T_p - T_c\right)_m} \qquad (12)$$

where *Tp* - the temperature at a heat source, and *Tc* - the temperature at a consumer. Subscripts *s* and *m* denotes simulated and measured values, respectively. In equation (1), we assume that *(Tp)s*=(*Tp)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 and relative errors along with standard deviation of average error for predicted supply temperature at consumers for the first considered time period (25-26 March) and the second considered time period (29-30 March)

Consumers No	First considered time period (25-26 March)				Second considered time period (29-30 March)			
	Node method		TERMIS		Node method		TERMIS	
	Relat. error (from eq.11)	Aver.error (standard deviation) [^{o}C]	Relative error (from eq.11)	Aver.errorv (standard deviation) [^{o}C]	Relat. error (from eq.11)	Aver.error (standard deviation) [^{o}C]	Relat. error (from eq.11)	Aver.error (standard deviation) [^{o}C]
101	0.15	0.29 (1.20)	0.11	0.2 (1.41)	-0.04	-0.06 (1.29)	-0.3	-0.46 (1.8)
102	0.35	0.86 (1.19)	0.32	0.79 (1.37)	0.23	0.46 (1.25)	0.04	0.08 (1.76)
103	0.24	0.53 (1.07)	0.19	0.21 (1.15)	-0.12	-0.09 (1.2)	-0.6	-0.46 (1.66)
104	0.001	0.01 (1.05)	0.03	0.03 (1.29)	0.02	0.02 (1.09)	-0.3	-0.35 (1.52)
105	-0.02	-0.02 (1.0)	-0.09	-0.15 (1.22)	-0.33	-0.41 (1.22)	-0.6	-0.83 (1.70)
106	0.28	0.88 (0.89)	0.24	0.73 (1.16)	0.27	0.83 (0.79)	0.13	0.41 (1.19)
107	0.02	0.02 (1.10)	-0.03	-0.03 (1.16)	0.05	0.06 (1.07)	-0.27	-0.33 (1.52)
108	-0.04	-0.03 (1.17)	-0.10	-0.07 (1.23)	-0.9	-0.4 (1.39)	-0.89	-0.79 (1.82)
109	0.29	0.52 (0.89)	0.24	0.44 (1.09)	0.28	0.52 (0.89)	0.02	0.13 (1.33)
110	0.35	0.63 (1.11)	0.32	0.58 (1.16)	0.35	0.63 (0.98)	0.26	0.26 (1.35)
111	0.29	0.82 (0.99)	0.26	0.72 (1.06)	0.18	0.46 (1.14)	0.01	0.02 (1.72)
112	0.34	0.48 (0.94)	0.32	0.45 (0.99)	0.31	0.52 (1.03)	0.11	0.18 (1.60)
113	0.45	0.94 (1.01)	0.01	0.03 (1.8)	0.35	0.54 (1.32)	-0.16	-0.94 (1.79)
114	0.52	2.46 (1.14)	0.51	2.41 (1.15)	0.52	3.02 (1.16)	0.45	2.6 (2.02)

The largest average and relative errors can be noted for industrial consumer 114 (see Table 1). The relative error, representing the quality of temperature value prediction, is higher than for other consumers for the first considered time period where a temperature wave is depicted. Whiles for the second considered time period with temperature impulses, the relative error is somewhat larger and for other consumers, especially for TERMIS software. The average error is also significantly higher for this consumer (i.e., 114) for both considered time periods and for both modelling approaches. As this error represents the quality in estimation of heat losses, the flow regime in pipelines should be examined closely. This consumer has extremely low velocity in the intake pipe (i.e., pipe that connects consumer substation to the network) over that considered time period. 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 Figs 5 and 6). It occurred due to the small heat load for the simulated days.

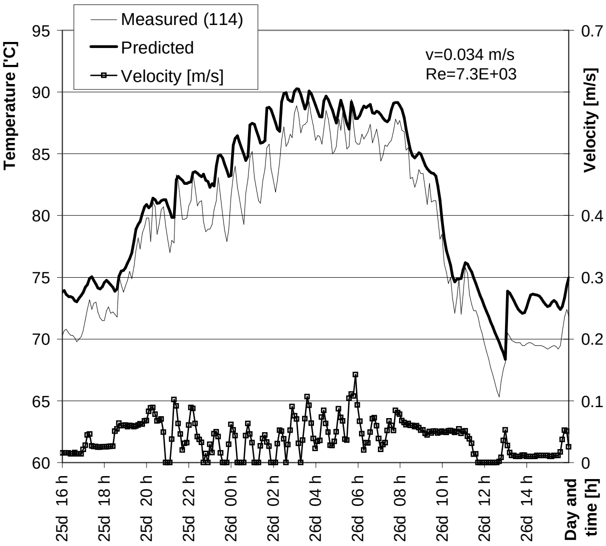

Fig 5. Temperature and velocity for consumer 114 for March 25-26 day

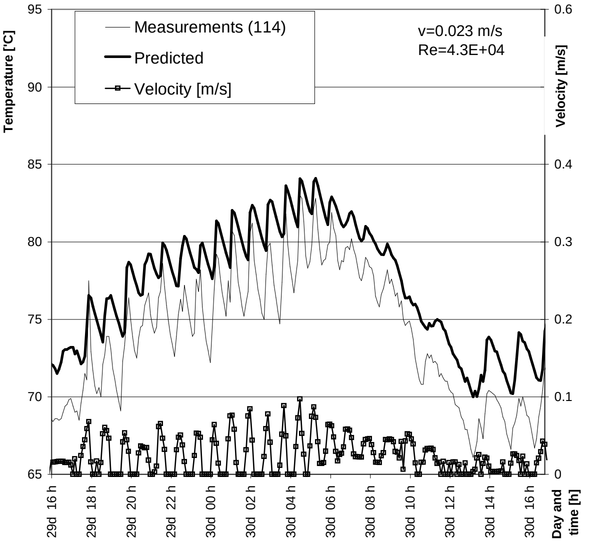

Fig 6. Temperature and velocity for consumer 114 for March 29-30 day

This causes high heat losses compared to other pipes, which described approaches are not able to represent correctly. The flow regime in the consumers' intake pipe greatly influences the quality of prediction. Other consumers (consumers 112 and 103) that are connected to the same network line (branch N06-N08-N09 in Fig 2) have smaller average error, i.e., less than 1°C, than consumer 114 (more than 2°C average error). Consumers 112 and 103 have much higher velocity in the intake pipe (in the order of 0.2-0.3 m/s), than consumer 114. 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 standard deviation, representing the measure of how accurate the time delay between a heat source and consumers is evaluated, has the value around 1 for both modelling approaches for the first considered time period (Table 1). However, for the second considered time period 29-30 March, the difference between the approaches is not uniform and TERMIS has somewhat larger value of standard deviation.

5. Results for Temperature fluctuations

In Figs 7-10, the propagation of steep changes in supply temperature and its prediction are detailed for second considered time period. 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 2). Velocity fluctuation at those consumers can be seen in Figs 7-10, 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 11). From Figs 7-10 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 be approximated as periodical, which at relative amplitudes of 10-30% produce a small variation in local heat flux quantities. This has no measurable effect on the average heat transfer according to study performed in (Benim *et al.* 2004). Thus, it would be appropriate to conclude that velocity fluctuations of such kind would not affect the fluid temperature significantly.

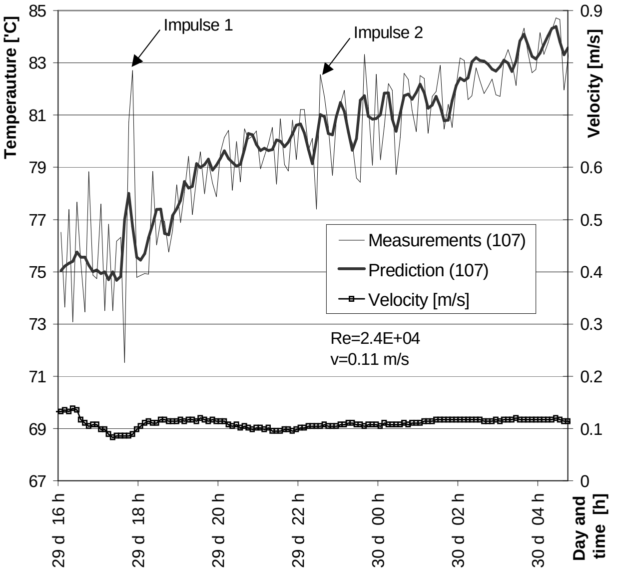

Fig 7. Temperature and velocity for consumer 107 for the second considered time period

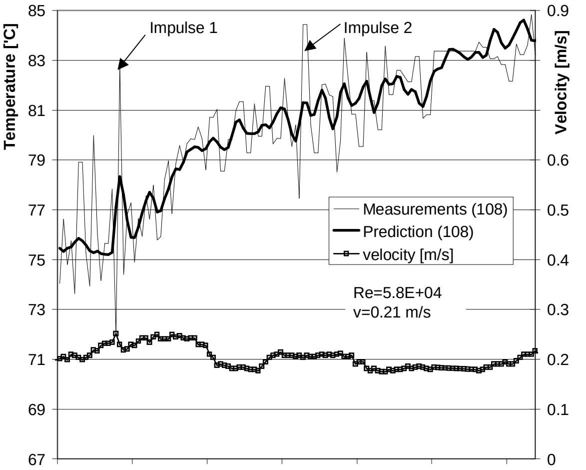

Fig 8. Temperature and velocity for consumer 108 for the second considered time period

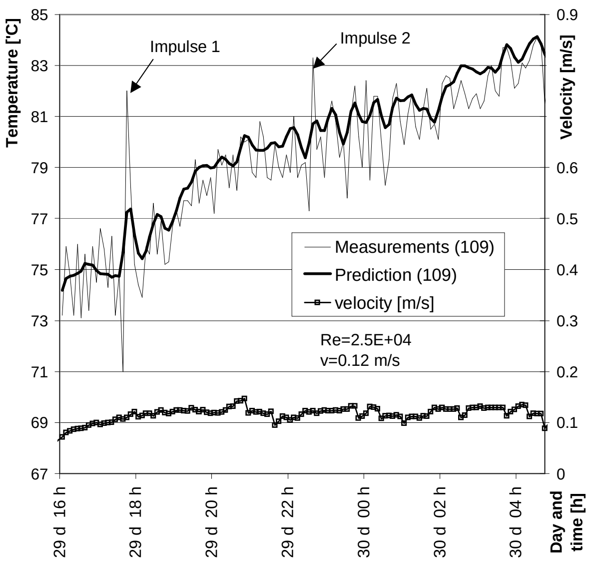

Fig 9. Temperature and velocity for consumer 109 for the second considered time period

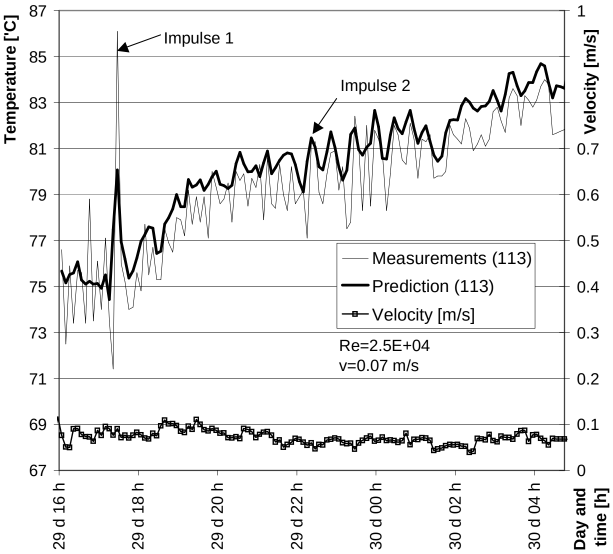

Fig 10. Temperature and velocity for consumer 113 for the second considered time period

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 4). The first impulse having value of 16^oC between the lowest and highest impulse points, introduces a deviation between the predicted and measured temperature higher than 4^oC. The second impulse (7.2^oC) produces a deviation between predicted and measured temperature higher than 2^oC, while the typical value of maximum scattering between those values is found to be within 2^oC, when the temperature changes were smaller than the impulses. The prediction of the above-mentioned impulses is shown in Figs 7-10 for consumers 108, 109, 107 and 113.

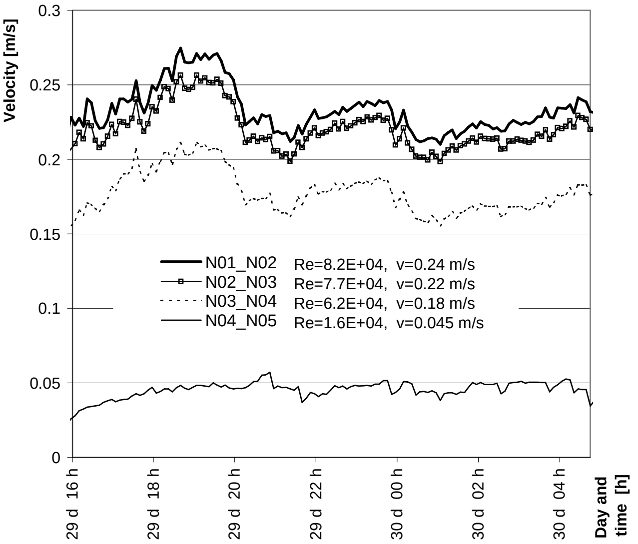

Fig 11. Measured velocity in the pipelines preceding consumers 107,108,109,113 for the second considered time period (The location of the pipelines is shown in Fig 2)

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

6. Conclusions

Two modelling approaches have been applied for simulation of a district heating system in Madumvej (Denmark). The transient temperature behaviour was simulated by the node method developed at the Technical University of Denmark and the commercial software TERMIS. The differences between two models are pronounced when the large flow rate variations were observed, as indicate the results obtained from the modelling of Madumvej district heating system. The difference in predictions obtained by the two models was insignificant for a relatively small and slow temperature increase.

The measured data from the district heating systems were applied for comparison of results obtained from modelling approaches. From this comparison, it could be concluded that the prediction of temperature values deviates significantly from the measured values in following cases: i) during relatively larger and sudden temperature changes at the heat source (e.g., an impulse of $8\text{-}16^oC$ produced over approximately 20 minutes) and ii) during periods with low velocities (of the order of 0.04 m/s and less). Based on the analysis of the temperature wave propagation through the network, it was noted that the temperature wave spread unevenly at different location in the network. The results indicate that the discrepancies between the predicted and measured temperatures are pronounced for the consumers located at distant pipelines.

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