Waste Water Recovery System with Heat Pump for Hot Water Preparation

Waste Water Recovery System with Heat Pump for Hot Water Preparation

R Červín[1] and T Matuška[2]

[1]Faculty of Mechanical Engineering CTU in Prague
[2]Universtiry Centre for Energy Efficient Buildings of CTU in Prague

radek.cervin@fs.cvut.cz

Abstract. Waste water heat recovery is currently one of the possible ways how to reduce energy performance of buildings. The mathematical model using specific heat pump parameters is presented in this article. The aim was to verify efficiency of the waste water recovery system with heat pump for domestic hot water heating in family houses. The model enabled to evaluate heat recovery effectiveness during a day cycle. The first set of simulations of a typical day cycle has shown that the heat pump with recuperation of waste water is not effective solution for family houses. However, it might be interesting for the objects with larger consumptions. Another simulations for these objects were performed and more promising results were reached.

1. Introduction

Energy for domestic hot water (DHW) preparation takes on significance in last decades due to reduction of space hating demand. The heat demand for hot water exceeds even 50 % of overall heat demand for retrofitted or new buildings. Thus heat recovery from the waste water could have a great potential for further increase of building energy performance. Regarding to whole year usage the waste water is relatively stable source of energy for further utilization. There are many technologies for heat recovery from waste water as it is described in [1]. Heat recovery using heat exchangers can be made locally or by central systems. Local heat exchangers preheat cold water and are usually are installed close to shower. Central heat exchangers can be used for preheating as well or it might be combined with waste water tank.

Another option is the usage of heat pumps. One possibility is to install wastewater tank on the boundary of the building. The waste water (WW) is accumulated in the tank and is continuously cooled down by the primary circuit of the heat pump and the heat is transferred to another application. The main advantage of this system is possible time gap between production of waste water and heat utilization. The tank is designed according to the waste water flow in a drain pipe. Position of the tank is usually in utility room or outside. It is not possible to keep waste water in the tank more than one day because of hygienic limitation. The waste water could have a relatively high temperature level from 25 °C to 35 °C. The second option is to recover the heat from larger sewage piping system with continuous flow but the temperature of waste water is lower in range of 10 to 20 °C depending on the time of the year. Examples of existing installations with promising results are in [2] and [3].

This paper is focused on the system with waste water tank placed on the boundary of the building which is cooled down by a heat pump and the heat is transferred into domestic hot water tank. The heat recovery from waste water is thus used for hot water preparation. Conventional heat pumps available on

the market allow to work with temperature from 20 °C to 25 °C of the wastewater. In case of higher temperature there is a need to install mixing valve in the primary circuit or to reduce the waste water temperature in the tank. On the **Figure 1** a scheme of analysed system is shown.
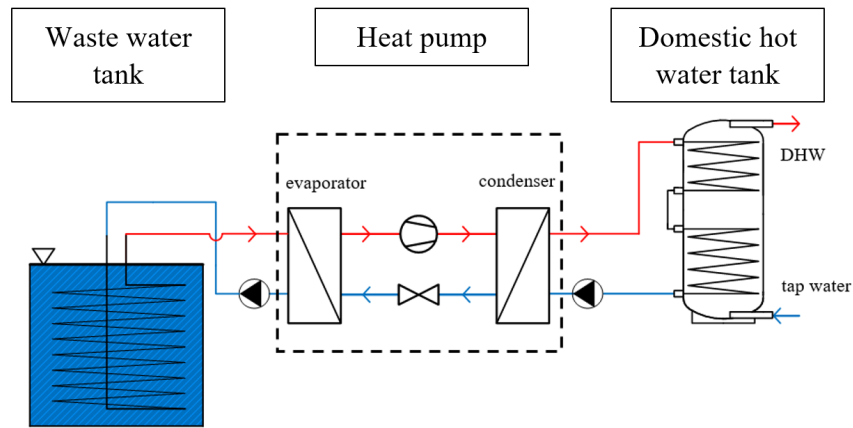

**Figure 1**. Scheme of wastewater heat recovery using heat pump

To evaluate the effectiveness of wastewater heat recovery system with heat pump the semi-empirical model of the heat pump has been developed based on the experimental testing. The model was further used for simulations of the heat recovery system during a typical day in several possible applications.

2. Experimental system

An experimental system has been built to test the heat recovery from waste water by conventional heat pump and domestic hot water preparation by recovered heat. The system is composed from the laboratory heat pump (**Figure 2**), insulated waste water tank and DHW tank. Nominal power of the heat pump is 5.5 kW for 0/35 °C. DHW storage tank with indirect heating (tube heat exchanger with surface 1.5 m^2) has volume of 144 l. WW tank has water volume of 200 l, an insulation of 100 mm and vertical coil with 1.5 m^2 was placed inside as heat exchanger.
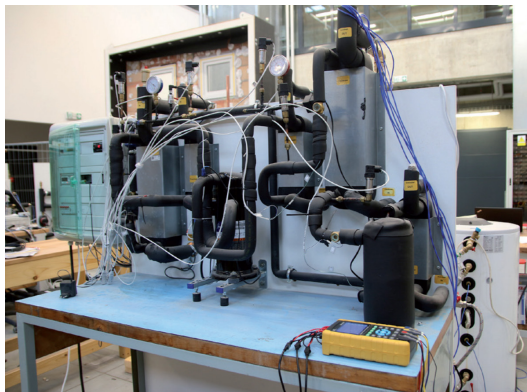
Figure 2. Laboratory liquid-liquid heat pump
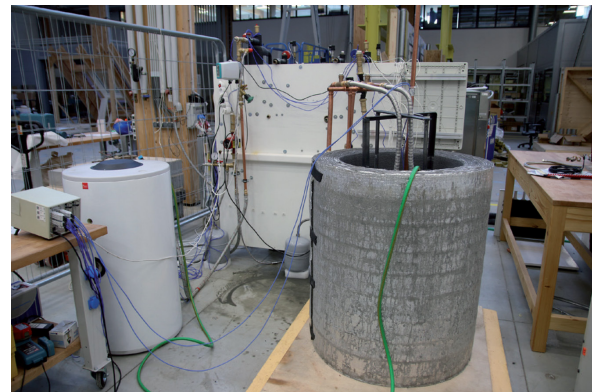
Figure 3. View of the experimental system in the laboratory

Following parameters were measured: refrigerant evaporation and condensation temperatures, temperatures in both tanks, flow in secondary circuit and power input of the compressor. All parameters were recorded in 4 sec time step. There were several cycles of waste water tank discharging coupled with charging of DHW tank. Initial temperature in DHW storage tank was always around 10 °C at the beginning of the testing cycle, while final temperature reached about 48 °C. Initial temperature in waste

water tank was around 33 °C and the tank was cooled down to level of 6 °C in the cycles. Each testing cycle lasted approximately 1 hour.

Several measurements series with various boundary conditions were made. Promising results were obtained with average *COP* of the heat pump around 4.0. High effectiveness of the system is influenced mostly by operation at favourable conditions (high initial temperature in WW tank and low initial temperature at DHW tank).

3. Mathematical model of the heat pump

To analyse the waste water heat recovery system mathematical model of the heat pump has been developed based on the experimental results. The model calculates compressor power P [W] and heat output Φ [W] of the heat pump according to inlet temperatures to the evaporator t_{ev1} [°C] and condenser t_{co1} [°C] according to polynomials below

$$P = A_P + B_P \cdot t_{co1} + C_P \cdot t_{ev1} + D_P \cdot t_{co1}^2 + E_P \cdot t_{co1} \cdot t_{ev1} + F_P \cdot t_{ev1}^2 \tag{1}$$

$$\emptyset = A_\emptyset + B_\emptyset \cdot t_{co1} + C_\emptyset \cdot t_{ev1} + D_\emptyset \cdot t_{co1}^2 + E_\emptyset \cdot t_{co1} \cdot t_{ev1} + F_\emptyset \cdot t_{ev1}^2 \tag{2}$$

Constant have been calculated by multiple regression function from all values obtained by testing in different experimental cycles. Heat output and power input of the heat pump modelled by polynomials and measured within given test cycle is shown in **Figure 4**. Modelled curve (dashed) of the heat output follows decreasing trend of the measured curve (solid) relatively well. At the beginning, the real power is influenced by the function of the electronic expansion valve. Therefore the polynomial function doesn't work correctly. At the end of the cycle the calculated heat output is lower compared to the real output of the heat pump because of limitation of the second order polynomial. The average value of the calculated heat output corresponds to the reality with the error of 10 %. On the other hand electric power input of the compressor is calculated with good accuracy during the whole experimental cycle. The model of the heat pump is possible to use for the simulation of typical day.
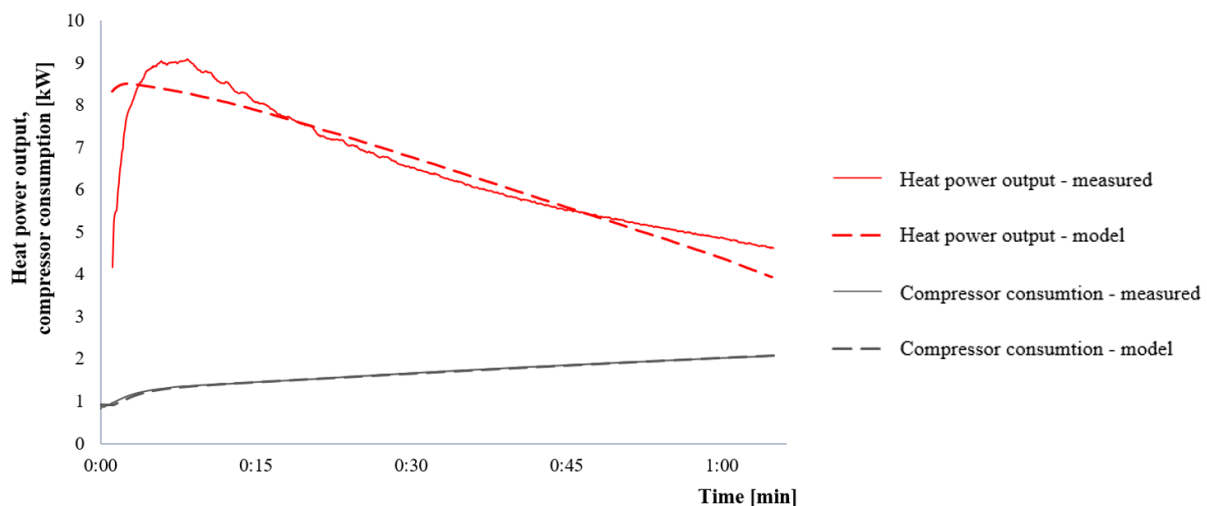
Figure 4. Comparison of the heat pump model with the results from experimental measurement

4. Simulation of a typical day in single family house

Volume of the tank for waste water was considered 180 l. DHW tank volume was considered identical as in testing 144 l. The specific heat loss 1.6 W/K for DHW tank and 1.85 W/K for WW tank both evaluated from testing were considered. All required boundary conditions for a typical day were defined as a day in the middle of the week with standard tapping, when operation of the WW tank is stable.

In **Table 1** water tapping profiles during a typical day are listed according to [4]. For each time in five minutes step an amount of drawn water to load is defined. The total amount of 45°C hot water to

load is 200 l per day, which corresponds with energy of 8.141 kWh. An energy consumption in each time step and volume of the 45 °C water could be calculated from given part from overall energy.

**Table 1.** Water tapping profile of the typical day according the [4] in single family house

9	Part from overall energy (%)	Energy consumption (Wh)	Type of the water tapping	Volume of the water (45 °C) (l)
7:00	0.9	73.3	small tapping	1.8
7:05	12.0	977.9	shower	24.0
7:30	0.9	73.3	small tapping	1.8
7:45	0.9	73.3	small tapping	1.8
8:05	30.9	2518.2	bath	61.9
8:25	0.9	73.3	small tapping	1.8
8:30	0.9	73.3	small tapping	1.8
8:45	0.9	73.3	small tapping	1.8
9:00	0.9	73.3	small tapping	1.8
9:30	0.9	73.3	small tapping	1.8
10:30	0.9	73.3	cleaning of the floor	1.8
11:30	0.9	73.3	small tapping	1.8
11:45	0.9	73.3	small tapping	1.8
12:45	2.7	220.0	short cleaning of the dishes	5.4
14:30	0.9	73.3	small tapping	1.8
15:30	0.9	73.3	small tapping	1.8
16:30	0.9	73.3	small tapping	1.8
18:00	0.9	73.3	small tapping	1.8
18:15	0.9	73.3	cleaning	1.8
18:30	0.9	73.3	cleaning	1.8
19:00	0.9	73.3	small tapping	1.8
20:30	6.3	513.4	long cleaning of the dishes	12.6
21:00	30.9	2518.2	bath	61.9
21:30	0.9	73.3	small tapping	1.8

Stratification wasn't considered in DHW tank nor in WW tank. Temperature of the drawn hot water was always 45 °C and temperature of the waste water coming to the WW tank was always 33 °C. ON/OFF control of the heat pump was considered according to the temperature in DHW tank with hysteresis. If the hot water temperature in the DHW tank dropped below 43 °C, heat pump started, until the temperature of 47 °C was reached.

Heat output and electric power input of the heat pump were calculated in each time step from the polynomial functions. Both variables (evaporating temperature t_{ev1} and condensing temperature t_{co1}) had to be estimated from mean temperatures in both tanks and then calculated by iteration process in each time step. The first estimation were average differences between mean temperatures in condenser and evaporator and mean temperatures in both tanks. Condensing temperature was defined as $t_{co1} = t_a + 9,5\,°C$ and evaporating temperature was defined as $t_{ev1} = t_o + 6,2\,°C$ (defined by evaluation of heat exchangers behaviour). Then the iteration process resulted from specific power of the heat exchangers UA [W/K] both in evaporator circuit (WW tank, experimentally tested) and in condenser circuit (DHW tank, taken from manufacturer's datasheet). After that heat output and

compressor power were evaluated and evaporator cooling power was calculated from these values. Although standardized draw-offs were given in 5 minutes time steps, the simulation has been performed in 1 minutes time step for better accuracy.

The chart in **Figure 5** demonstrates the course of temperatures in both tanks for standardized hot water draw-offs. The heat output and power input of heat pump are also shown. When the hot water is drawn the mean temperature in DHW tank decreases and in the same moment mean temperature in the WW tank increases because the used hot water goes to drain (storage of hot water and delayed input to WW tank wasn't considered in calculations). Cold water enters the DHW tank from water mains with temperature 10 °C. On the other side in the WW tank volume of 180 l is always kept, which means the same amount of added new waste water is drained to sewer system. Actual temperature in the WW tank is mixed with new wastewater of 33 °C in each time step.
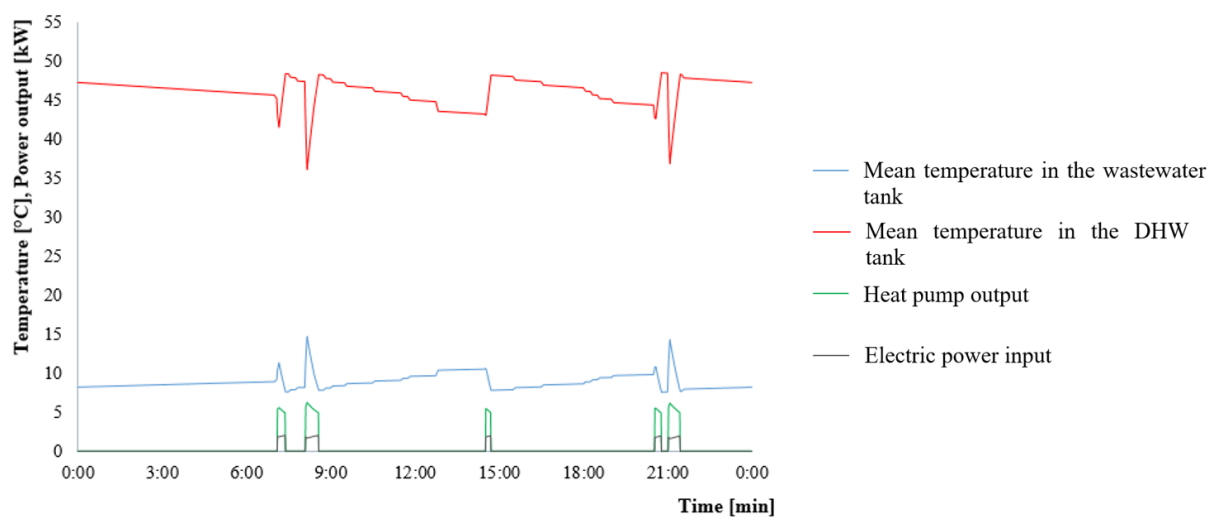
Figure 5. Simulation of mean temperatures in the DHW tank and in the WW tank and heat pump during typical day in a single family house

In the Table 2 an energy balance of the whole recovery system is reviewed. The value of COP_{HP} is almost 30 % lower than result obtained from experimental measurement (COP = 4.0)**.** The main reason is that charging DHW tank from low temperature 10 °C is much more favourable than continuously keeping the temperature on the level of 45 °C. The temperature in DHW tank was practically never bellow 36 °C. Moreover, temperature in the WW tank is also lower compared to the experimental measurement and was never above 15 °C. Both of these facts worsen total effectiveness of the system. Another important fact is that requirement for 45 °C wasn't always fulfilled. Total amount of undelivered energy is 0.57 kWh. This energy must be covered by backup energy source. Electrical resistance heater was considered. The usage of the backup heater also decreases efficiency of the whole system. Overall COP of the recovery system (heat pump + backup heater) is 2.68.

Table 2. Energy summary of the typical day

|	
Overall energy consumption of the compressor	2.84 kWh
Overall power output from the heat pump	8.57 kWh
COP_{HP}	3.02
Missing energy (for requirement of 45 °C)	0.57 kWh
Wastewater tank – gains	0.49 kWh
DHW storage tank – heat losses	0.98 kWh
Overall COP of the system	2.68

5. Simulation for small sport center

Another simulation was made for building with regular operation and higher demand for DHW than in case of single family house. Considered building was a small sport center. Number of training session was 8 per day – 3 trainings in the morning and 5 in the afternoon. There were average 20 participants on each training. All of them took shower after their session in 4 showers. Total flow was 24 l.min^{-1}. Volume of the DHW tank was 200 l and volume of the wastewater tank was 500 l. Overall energy consumption was 125 kWh per day, but heat pump delivered only 59.5 kWh (preheating system). The heat pump operates in stable periods of the load and average temperature in WW tank reaches higher levels compared to case of family house. The $COP = 4.83$ was achieved in this type of operation. In the **Figure 6** typical day cycle is presented. It is obvious that required 45 °C temperature is not reached and the heat pump has preheating function only.
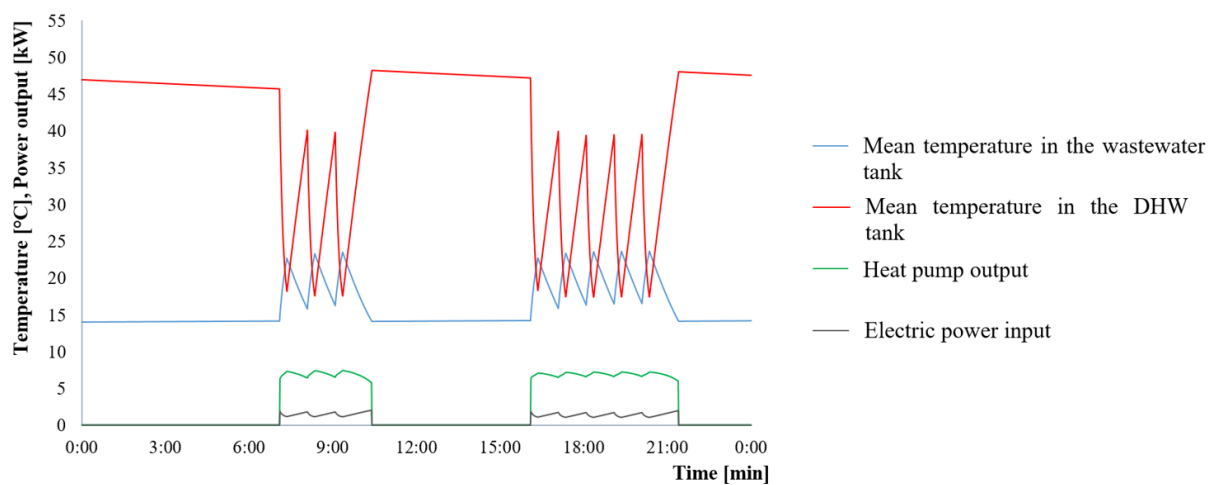
Figure 6. Simulation of wastewater heat recovery system using heat pump in a small sport center

6. Simulation for building with continuous operation

In case of building with continuous load of hot water e.g. a spa with pool or big hotel with wellness, the conditions could be also favorable for such heat recovery system with a heat pump. Temperatures in both tanks, heat output and power input of heat pump are stabilized during continuous operation. Graph in the **Figure 7** shows the course of these quantities during a typical day. For given 5.5 kW (B0/W35) heat pump, the best results were reached with constant flow of hot water of 4 l.min^{-1}. It is obvious that
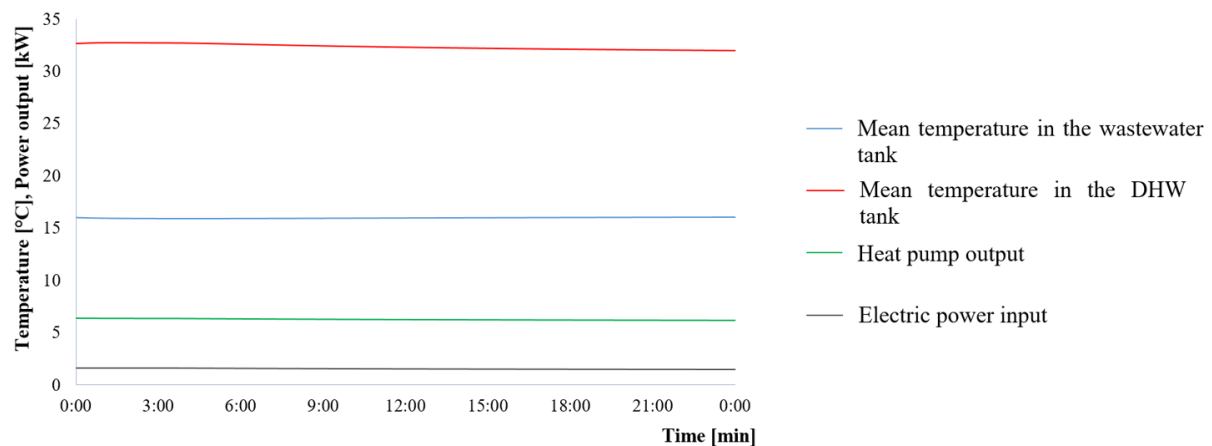
Figure 7. Simulation of waste water heat recovery system using heat pump in building with continuous load of hot water

for higher flow higher power of the heat pump is needed. Temperature of the DHW preheating tank was stabilized around 33 °C and temperature in the WW tank was constantly around 16 °C. Average heat pump output was 6.3 kW and electric power input was 1.6 kW. *COP* of the system in this case was 4.2.

7. Conclusion

According to the results obtained from the testing on experimental system, the simplified mathematical model of the heat pump system was built. The model has been used for simulation of hot water preparation by heat recovery from waste water by the heat pump during a typical day in single family house. The effectiveness of the whole heat recovery system has been evaluated. The results demonstrated that the waste water recovery system with the heat pump does not reach high effectiveness in the single family house. Maximal daily *COP* = 2.68 was reached. As further simulation analyses have shown, significantly higher efficiency could be achieved in buildings with higher and uniform DHW consumption.

Acknowledgments

References

[1]   Hepbasli A, Biyik E, Ekren O, Gunerhan H and Araz M 2014 A key review of wastewater source heat pump (WWSHP) systems *Energy Convers. and Manag.* **88** 700–22 ISSN 01968904. Available from: http://dx.doi:10.1016/j.enconman.2014.08.065

[2]   Schmidt F 2008 Sewage water: interesting heat source for heat pumps and chillers *Paper 9th Int. IEA Heat Pump Conference (*Switzerland) 12

[3]   Seybold Ch, Brunk M F 2016 In-house waste water heat Available from: http://www.rehva.eu/fileadmin/REHVA_Journal/REHVA_Journal_2013/RJ_issue _6/P.18/18-21_Seybold_RJ1306.pdf

[4]   European Commission, Directorate-general for energy and transport, Directorate D. M/324 Mandate to CEN and CENELEC for the elaboration and adoption of measurement standards for household appliances: Water-heaters, hot water storage appliances and water heating systems. Brussels, 2002. Available from: http://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=select_attachments.download&doc_id=1244