UDC 532.13:620.179.13:519.61
Original scientific paper
Received: 03.09.2001.

Visualization of the crude oil melting process

Tomislav Tomiša, **Igor Kuzle** and **Sejid Tešnjak**
Faculty of Electrical Engineering and Computing, Department of Power Systems, University of Zagreb,
Unska 3, HR-10000 Zagreb, CROATIA
e-mail: tomislav.tomisa@zvne.fer.hr; igor.kuzle@zvne.fer.hr; sejid.tesnjak@zvne.fer.hr

SUMMARY

An experiment in real condition was performed to support the development of a new designed crude oil pumping facility on the tank wagon decanting station. Since the pumping process failed during the previous tests, the visualization of the heating process inside the tank was required to find out the optimized parameters for the improved automatic pumping algorithm. The 32 temperature sensors were installed inside the tank wagon before loading with oil, and connected to the PC based data acquisition system. The measured data collected during the whole heating/pumping process were graphically presented to visualize the time depended 3-dimensional oil temperature distribution inside the tank. Finally, the successful reconstruction of pumping facility was made based on those results.

Key words: *heating process of crude oil, tank wagon, temperature field, data acquisition, process visualization.*

1. INTRODUCTION

At the ambient temperature below zero degree a crude oil becomes solid. Since even at the normal ambient temperature the crude oil is in gel condition, it has to be preheated at least up to *45°C* to melt it before pumping. Once loaded, wagon tank can be discharged at the destination only after the whole content is melted performing appropriate heating procedure.

Generally there are two principles for crude oil melting before decanting the tank wagon:

- indirect heating - the tank is heated from outside using a hot water or hot air until the tank content becomes enough liquid to be emptied trough a drain pipe,
- direct heating - the tank content is heated from inside using a special heating body which penetrates into the oil through the upper hatch of the wagon and it pumps-out the melted content.

Since the indirect heating cannot be performed in the open area (it requires a large closed and heated room) the direct heating method has an advantage because it requires significantly less energy consumption for oil melting, but it uses much more complex decanting equipment. The experimental prototype of such decanting facility consists of the following subsystems (Figure 1):

- mechanical arm (motor-controlled in three axes) carrying the dip-in heating body including the suck-in and sprinkling pipes,
- pumping subsystem including the steam heat exchanger provided with the appropriate control valves,
- control cabinet with the PLC-based process control unit.

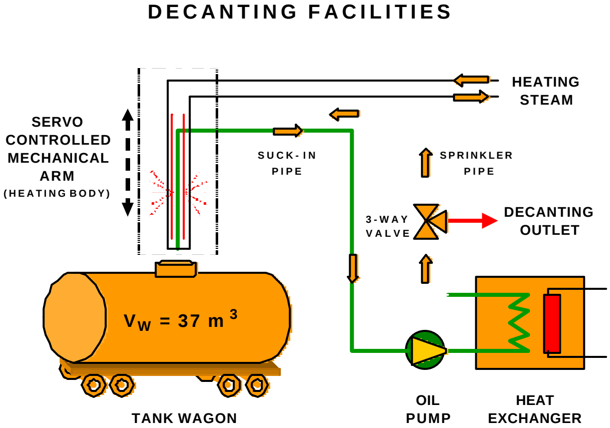


Fig. 1 Schematic of an experimental decanting facility

The oil heating process is realized in three phases: pre-heating, circulation and decanting using specially developed heating/pumping facility mentioned above. During the pre-heating phase a certain amount of the oil around the dip-in heater in the tank wagon should be melted to enable oil circulation.

In the second phase oil is pumped out and heated in temperature controlled heat exchanger up to *80°C*. Such heated oil is returned back into the tank wagon using sprinklers which will melt the rest of the unmelted oil. The circulation is performed until the total content of the tank is heated up to *45°C*. Finally, the melted oil is pumped out during the third phase (decanting).

2. EXPERIMENT

Since the complete heating process has to be performed automatically controlled by PLC unit, the appropriate relations between the time duration and oil temperature for each phase should be obtained from the experiment to parameterize the PLC program.

The essential problem is to determine the appropriate time duration of pre-heating phase. If the chosen time is too short the circulation process cannot start successfully, while if the pre-heating duration was too long the whole decanting process cannot be ended in a disposable time period.

The successful start of the circulation pump depends on the amount of the melted oil that should be enough to fill the complete circulation pipe system without air.

The duration times of the pre-heating (T_1), circulation (T_2) and pumping (T_3) phases are the parameters which have to be determined depending on the outside temperature, starting oil temperature and the thermal characteristics of the oil.

A total process time is limited with decanting schedule time T_{max}:

$$T_{tot} = T_1 + T_2 + T_3 < T_{max} \tag{1}$$

The pre-heating time T_1 depends on:

- thermal characteristics of the oil,
- starting oil temperature (J_0),
- power of dip-in heating body (P_1),
- heat transfer conditions around heating body.

The circulation time T_2 is determined by the sprinkling subsystem characteristics (pressure, temperature) but it also depends on the initial oil temperature and thermal characteristics, tank volume and temperature required for pumping.

As mentioned before, to ensure successful start of circulation, a certain amount of oil volume (V_1) have to be pre-heated at the temperature (J_1) using heat quantity:

$$Q_1 = m_1 \cdot c_p \cdot DJ \tag{2}$$

where: m_1 stands for mass of pre-heated oil ($V_1 \cdot r$) [kg]; c_p is specific heat [$kJ/kg°C$]; DJ stands for temperature difference (J_1-J_0) [$°C$].

Since the total input heat, during the pre-heating phase, is given by:

$$Q_1 = P_1 \cdot T_1 \tag{3}$$

the pre-heating time can be expressed as:

$$T_1 = \frac{Q_1}{P_1} = \frac{V_1 \cdot r \cdot c_p \left(J_1 - J_2\right)}{P_1} \tag{4}$$

It can be seen that duration of the pre-heating time, taking into account given conditions, is determined by the volume V_1 that generally is not known. This is the reason why the experiments in the real conditions are performed to estimate a minimal duration of the pre-heating time which for given conditions ensure the successful start of the circulation phase.

The circulation time T_2 depends on the rated values of the pumping subsystem (heating power, pump capacity), as well as on the oil thermal characteristic and the total tank volume.

The pumping time T_3 is determined with the pump rated capacity and depends on total tank volume.

3. EXPERIMENT DESIGN

The basic task of the experiment was to find out the oil temperature distribution inside the tank during the heating process. The tank wagon of $37\ m^3$ capacity ($F\ 2.8 \times 6\ m$) was used for the experiment.

The characteristics of the prototype plant are: pre-heater power $P_1 = 21\ kW$, tank volume $V = 37\ m^3$, low pumping temperature *45°C*, heated oil output temperature *100°C*.

For oil temperature measurement at the certain positions, 29 temperature sensors are placed inside the tank before oil loading, as shown in Figure 2.

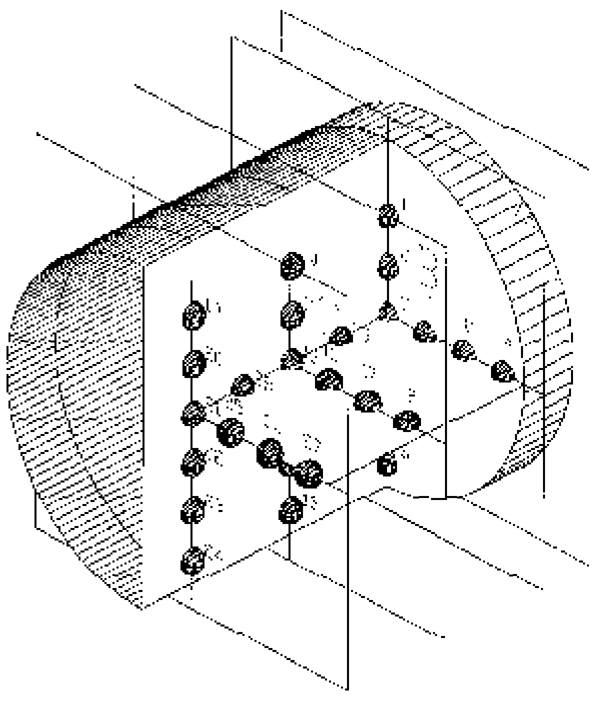


Fig. 2 Temperature sensors positions

Since the tank is symmetrical, only one quarter of the tank was provided with the sensors that are installed using a special mounting construction in three vertical cross-section planes of the tank (Figure 3):

- cross-section A-A: at the distance of *0.5 m* from the center of the tank,
- cross-section B-B: at the distance of *1.5 m* from the center of the tank,
- cross-section C-C: at the distance of *2.5 m* from the center of the tank.

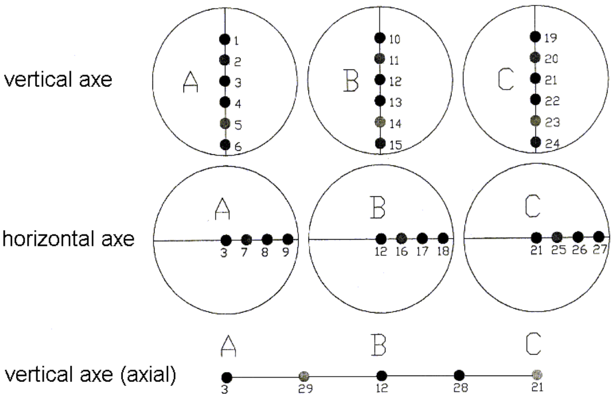


Fig. 3 Sensors positions in vertical cross-section planes of the tank

In each cross-section 9 sensors are placed in two axes:

- vertical axis: 6 sensors at intervals of *0.4 m*
- horizontal axis: 3 sensors at intervals of *0.4 m*

Between each cross-sections 2 sensors are placed in the central axis at the distance of *1.0 m* and *2.0 m* from the center of the tank. One movable sensor is placed near the inlet of the suck-in pipe in the tank.

Additionally, the outside tank temperature was measured using the sensor placed on the outside tank surface.

Specially designed 32-channel data acquisition system is used to collect temperature data during the heating process (Figure 1). The data are sampled continuously, but mean values are calculated every minute and stored in the file for post processing. The values of the actual pump current and rotating speed, input pressure and heated oil output temperature are also collected at certain periods of interest with the sampling rate of *50 ms* for the analysis purposes.

4. RESULTS OF EXPERIMENT AND PROCESS VISUALIZATION

The time-temperature profiles are plotted using data recorded during the progress of the experiments. The conditions before the start of the pre/heating phase were:

- outside temperature *0 °C*
- mean oil temperature *< 45 °C*

and the progress of the described experiment was as follows:

- pre-heating start time:
  10:40 h $T_1=0$
- duration of pre-heating up to:
  12:24 h $T_1=1h\ 44\ min$
- circulation start time:
  12:24 h UNSUCCESSFUL
- prolongation of pre-heating up to:
  13:00 h $T_1=2h\ 20\ min$
- retry of circulation at:
  13:00 h SUCCESSFUL
- circulation up to:
  15:24 h $T_2=1h\ 36\ min$

Total experiment duration: *4h 44 min.*

The time various temperature fields inside the tank is constructed on the basis of the recorded data. Since only one quarter of the tank volume was covered with placed sensors, the corresponded data are mirrored to obtain an image of the whole tank volume. Such arranged data are used to obtain the isothermal lines in the corresponded horizontal and vertical planes.

The calculation is made using sophisticated Kirighin algorithm on electronic computer (PC). These calculated data are used as input data for a volumetric time various temperature field reconstruction. An example of the measured temperature field (at the start of the experiment, at the beginning of the circulation and at the end of the experiment) through the vertical cross-section of the tank is shown on Figure 4.

From already calculated temperature field inside the tank it is possible to calculate volume of the given oil temperature at every time instant (Figure 5).

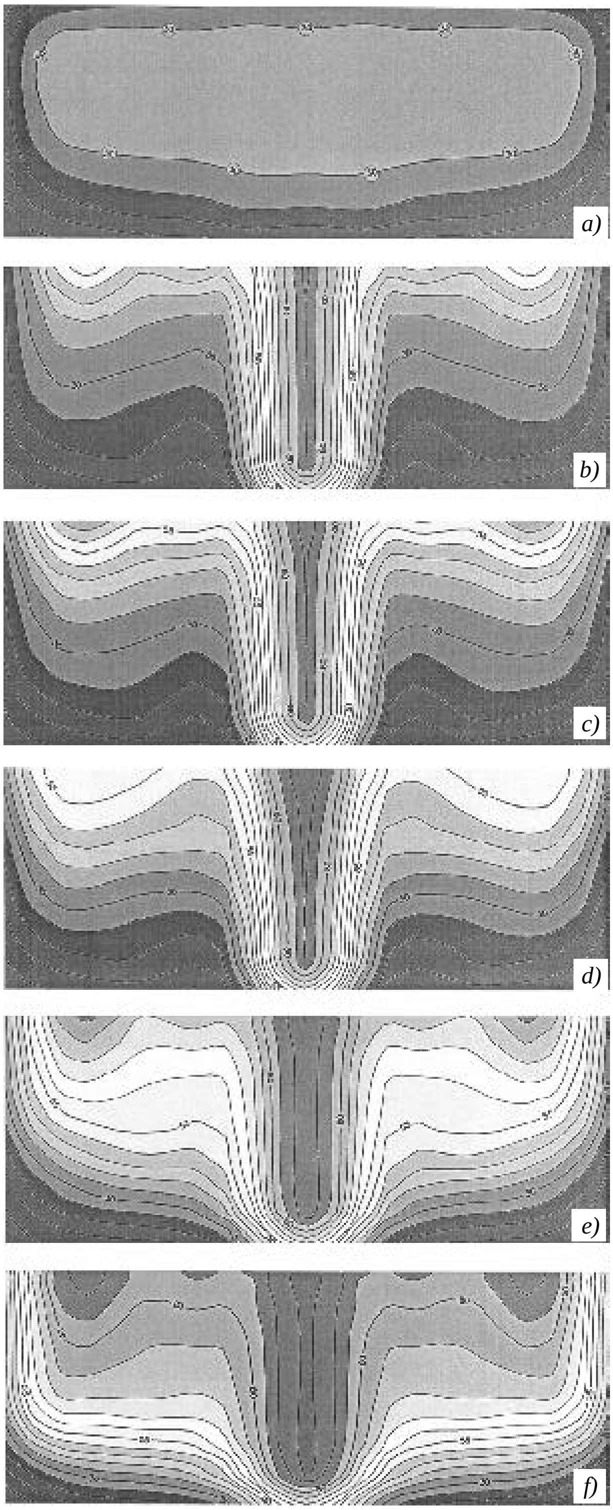
5. MODELING OF HEATING PROCESS

A heating process model is based on the energetic calculations (source for physical characteristics of crude oil was GOST standard 10585-75). As the range of an interest was the temperature region (*0-100°C*), the mean values are used: specific heat of oil ($c_p=1.95\ kJ/kgK°C$) and a specific density of oil ($r=900\ kg/m^3$).

The initial conditions for the described experiment (before taking a pre-heater in the tank) are calculated from the measured data using the mentioned temperature field reconstruction algorithm:

- mean temperature of a cold oil envelope:
  $J_h=20°C$ (*70 %* of oil volume),
- mean temperature of a warm oil substance:
  $J_t=27°C$ (*30 %* of oil volume),
- mean temperature of the total oil volume:
  $J_0=(20\cdot0.7+27\cdot0.3)=22°C.$

The minimal duration of the pre-heating phase which ensures a successful circulation after the cold start ($J_s<45°C$), as derived from performed experiments, should be $T_1=2.5\ h$, with input heat amount of $W_1=189\ MJ$. From the reconstructed temperature field, the mass of the oil heated above *45°C* after *2.5 h* is: $m_1=V_{45}\cdot r=5.8\cdot900=5220\ kg$. Since the pre-heating influences only a warm oil substance, the required heat amount to warm the mass m_1 from *27°C* to *45°C* is: $Q_1=m_1c_p(J_1-J_t)=5220\cdot 1.95\cdot(45-27)=183\ MJ$. This is well corresponded with the amount of the input heat W_1 (*189 MJ*).



a) starting condition (T_1=0)
b) T_1=30 min
c) T_1=60 min
d) T_1=120 min
e) T_1=180 min
f) T_1=270 min

Fig. 4 Temperature field inside the tank

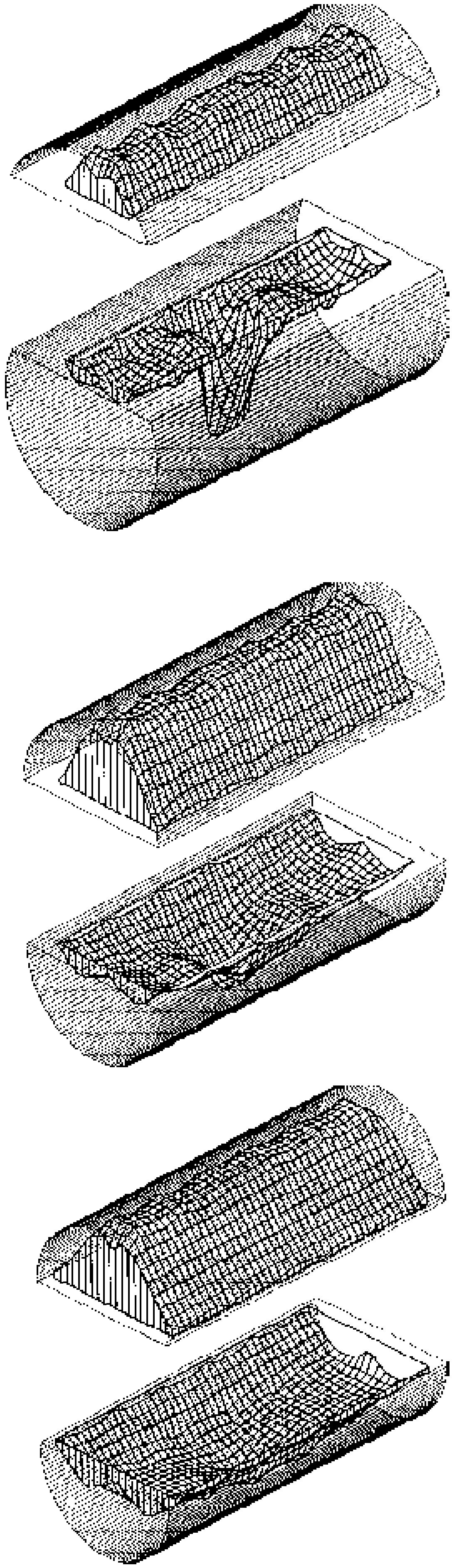


Fig. 5 Volume of melted oil (t=2.5h, t=4h)

Using temperature field reconstruction algorithm, the volumes of oil heated above *45 °C* are calculated at the certain time instants:

- at the beginning of the circulation: $V_{45(t=2.5h)}=5.8\ m^3$
- after 30 min. of proceeded circulation: $V_{45(t=3.0h)}=13.9\ m^3$
- after 90 min. of proceeded circulation: $V_{45(t=4.0h)}=19.4\ m^3$

The mean temperatures of these volumes are determined by correspondent time-temperature profiles:

- at the beginning of the circulation: $J_{s(t=2.5h)}=45°C$
- after 30 min. of proceeded circulation: $J_{s(t=3.0h)}=55°C$
- after 90 min. of proceeded circulation: $J_{s(t=4.0h)}=74°C$

The calculations of required heat are:

* after *30 min.* heated volume of $13.9\ m^3$ occupies practically only initial oil warm substance (about 30% of tank volume). Assuming a very low thermal conductance of the oil, there will be no changes in the oil temperature, ($J_t=27°C$), outside this heated volume, so:

$$Q_{30}=V_{45(t=2.5h)}\cdot r\cdot c_p\left[J_{s(t=3.0h)}-J_{s(t=2.5h)}\right]+ \\ +\left[V_{45(t=3.0h)}-V_{45(t=2.5h)}\right]\cdot r\cdot c_p\left[J_{s(t=3.0h)}-J_t\right]= \\ =500\ MJ$$

and the calculated mean heating power:

$$P_2=\frac{Q_{30}}{0.5h}=278\ kW$$

* after *90 min.* heated volume of $19.4\ m^3$ occupies particularly initial cold oil envelope. Assuming a very low thermal conductance of the oil, there will be no changes in oil temperature ($J_h=20°C$), outside this heated volume, *so* $Q_{90}=984\ MJ$ and the calculated mean heating power is:

$$P_2=\frac{Q_{90}}{1h}=273\ kW$$

The comparison of the calculated mean heating power confirms heating energy balance i.e. reconstructed temperature fields. Next calculation will be made using mean heating power value: $P_2=275\ kW$. Since heated oil output temperature is $J_i=100°C$, this is also a theoretical value which could be achieved inside the tank neglecting cooling losses. Recorded time-temperature profile can be approximated, assuming an exponential law of temperature rise in oil warm substance, as:

$$J_s=J_i-\left[J_i-J_{s(t=2.5h)}\right]\cdot e^{-0.5t_r}=100-55e^{-0.5t_r} \quad (5)$$

where t_r is heating time in circulation mode (hours).

A total time from the start of the experiment is then $t=T_1+t_r$. After *90 min.* of heating ($t=2.5+1.5=4\ h$) in tank there is $19.4\ m^3$ heated oil of mean temperature *74°C* and $17.6\ m^3$ oil of mean temperature *20°C* (rest of a cold envelope). Let's make prediction using exponential law - in next *90 min.* of heating ($t_r=3\ h$) the mean oil temperature will raise up to *88 °C*. During *90 min.* of circulation the energy brought into the tank is $W=P_2\cdot 1.5\ h=275\ kW\cdot 1.5\ h=1485\ MJ$, consisting of *476 MJ* used for warm oil substance heating and *1009 MJ* used for cold oil envelope heating. The cold oil envelope then achieves the temperature of *53°C* at which oil viscosity satisfies pumping conditions.

6. CONCLUSION

In order to heat the tank oil contents up to the required temperature, total circulation time should be $T_2=180\ min=3\ h$ which gives the total heating time of *5.5 h* (pre-heating $T_1=2.5\ h$+circulation $T_2=3.0\ h$). Since the process control is based only on the predefined duration of the pre-heating and circulation times, as functions of initial oil temperature (no information are returned from the tank), a change of the pump input pressure should be used as the measure of the circulation set-up efficiency.

7. REFERENCES

[1] Heavy Oil Decanting Station - Prototype, P&I Diagrams, INA-ROSS, Zagreb, 1995.

[2] Petrol Plant GRUŠOVAJA Novosibirsk, Project No. M-50-92, INA-ROSS, Zagreb, 1992.

[3] MATRIXX/PC, Digital Signall Processing Module, Ver. 8.0, Integrated Systems Inc., 1990.

[4] SURFER Access System, Ver. 3.0, Golden Software, 1987.

[5] Energy-saving Activities by Improving Melting Method of Ductile Segment Casting Line, TSY Circle, Manufacturing Section No. 1, Onkajima Plant, Kubota Ltd., The Energy Conservation Center (ECC), Japan, 1998.

VIZUALIZACIJA PROCESA TOPLJENJA TEŠKIH DERIVATA

SAŽETAK

Proces pretakanja teških derivata (mazuta) iz cisterne u neposrednoj je vezi sa zagrijavanjem i pumpanjem. U tu se svrhu koriste posebna postrojenja, obièno automatski upravljana. U radu je razrađen i opisan proces zagrijavanja i pretakanja na naèin da isti može biti automatski vođen programibilnim logièkim automatom (PLC). Za potrebe identificiranja parametara za automatsko vođenje neophodno je poznavati fizikalna zbivanja (pojave) u cisterni tijekom procesa zagrijavanja. Da bi razvijeni algoritam vođenja bio što vjerodostojniji, dakle da bi što vjernije oslikavao realno stanje, naèinjeno-izgrađeno je prototipno postrojenje (cisterna) te razvijen odgovarajuæi matematièki odnosno simulacijski model. Modeliranje procesa zagrijavanja temeljeno je na tzv. energetskom proraèunu u kojem su za izvorište podataka korištena fizikalna svojstva mazuta upotrijebljenog tijekom provedbe eksperimenta (Standard-norma GOST 10585-75).

Realan uvid u stanje procesa u cisterni nije bilo moguæe vidjeti zbog neprozirnosti mazuta te je odluèeno cisternu opremiti određenim brojem temperaturnih osjetnika kako bi se dobila vremenska i prostorna raspodjela temperature u cisterni tijekom eksperimenta. Nakon provedenih eksperimentalnih istraživanja (mjerenja), rezultati su uspoređeni s odgovarajuæim rezultatima teorijskih proraèuna. Na temelju izmjerenih vrijednosti temperatura, korištenjem raèunala, dobivene su izotermne linije po pojedinim presjecima cisterne, a zatim su ti podaci iskorišteni za izraèunavanje prostornog temperaturnog polja. Rezultati istraživanja razmatranog problema pokazali su, unatoè naèinjenim zanemarenjima u teorijskim razmatranjima, dobru podudarnost eksperimenta i odgovarajuæeg teorijskog modela.

Kljuène rijeèi: *proces zagrijavanja nafte, vagon cisterna, temperaturno polje, prikupljanje podataka, vizualizacija procesa.*