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Modelling a solid fuel unit for soil warming up before its exploitation

Anton Sinitsyn[1,*], *Liliya* Mukhametova[2] and *Alexander* Korobeinikov[1]

[1]Department of Heat and Gas and Water Supply, Vologda State University, Lenina str. 15, 160000, Russia
[2]Kazan State Power Engineering University, Kazan, Russia

Abstract. This work continues the previous studies on energy-efficient technologies and devices for thawing frozen soils during repair and construction works. It proceeds with the multi-year research on development of efficient devices for emergency repairs. The possibility of using a solid fuel back-draft furnace for accelerated heating of various types of soils is considered. Analysis of the existing devices is presented, the performance criteria are determined, computer modelling of the developed unit and heat and mass transfer processes for the most common types of soils are carried out.

1 Introduction

The study of properties of thawing soils is relevant due to intensive development of the permafrost zones. Research on thawing soils is important for many areas of civil and industrial construction, which are necessary to ensure the operation reliability of facilities constructed according to the second principle (foundation soils are used in thawed or thawing conditions), pipelines and roads in the permafrost zone.

Forecast of deformations is a rather complicated task since frozen soils have multicomponent compositions and differentiate in thawing conditions, and draw during thawing depends on many factors. So it requires further improvements.

A lot of research works on thermo-physical properties of frozen soils during thawing and compaction were conducted within about a hundred-year period. Thawed soil was studied by the Russian (N.A. Tsytovich, G.I. Lapkin, A.E. Fedosov, V.P. Ushkalov, S.S. Vyalov, Ya.A. Kronik, L.T. Roman, Yu.K. Zaretsky, M.N. Goldstein, I.N. Votyakov, V.F. Zhukov, G.V. Porkhaev, L.N. Khrustalev, E.P. Shusherina, G.I. Pakhomova, A.M. Pchelintsev, M.F. Kiselev, V.D. Ponomarev, E.D. Ershov, V.Z. Khilimonyuk and others) and international (Morgenstern N.R., Smith L.B., Crory F., Chamberlain E.J., Gow, Luscher A.J., McRoberts E.C., Harris C., Nixon J.F., Eigenbrod K.D., Keil L.D., Nillsen N.M., Gupta R.C., Speer T.L., Watson G.H., Ryde'n C.G. and others) scientists.

Issues of increasing the efficiency of uninterrupted heat supply sources at low temperatures, and, in particular, fossil fuel combustion processes, are relevant and were previously studied in [1–6]. The use of various fuels and intensification of fuel combustion processes in power plants, the creation of conditions for the complete combustion of fuel-air mixture due to optimal geometric arrangement of the furnace space, etc. are the examples of increasing the efficiency of thawing frozen soils.

We turn the attention to the studies [7,8], which describe in more detail the main devices, methods of thawing and methods for calculating transition phases during heating of a frozen structure. The work [9] presents an overview of the existing patents and commercial devices for elimination failures of utility systems in frozen rocks, as well as factors affecting the heat and mass transfer process. It can be concluded that the process of thermal conductivity in soils during thawing largely depends on humidity, density, soil type, cryogenic texture, mineral composition, changes in filtration coefficient, thawing rate, moisture outflow conditions, etc.

The issue of creating an efficient thawing method in the conditions of development of permafrost zones remains relevant from both practical and scientific points of view.

2 Review of the existing devices and analysis of its efficiencies

Soil exploitation associated with digging trenches in temperature conditions below zero degrees Celsius is complicated by the need for preliminary preparation and warming up of frozen soil.

In urban conditions, in the presence of a large number of active cable lines and other underground utilities, the use of pneumatic instruments (jackhammers, crowbars, wedges, etc.) is impossible due to the risk of mechanical damage to existing cable lines and other underground utilities. Therefore, the frozen soil must be pre-warmed before excavation work in the area of existing cable lines so that further work is carried out without the use of pneumatic instrument. The most

* Corresponding author: sinitsyn.science@mail.ru

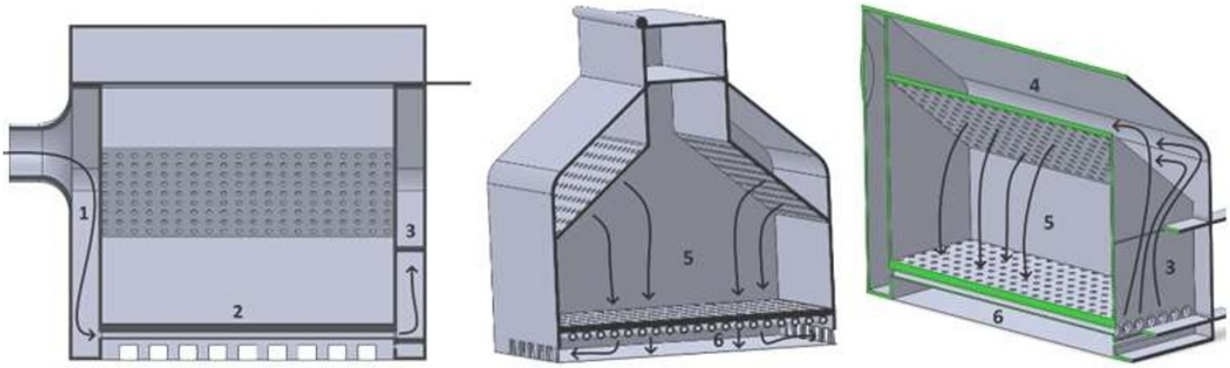

Fig. 1. Three-dimensional space model of a solid fuel furnace with back draft.

common methods of artificial thawing are thermal and electrothermal methods.

We bring into focus the following methods of soil heating during excavation in the autumn-winter period: electric reflex furnaces; electric horizontal and vertical steel electrodes; controlled fire; chemical defrosting; the use of steam and water needles; hot running coolant (sand, slag, gravel, soil, road waste - asphalt crumb); tubular electric heaters; high frequency currents; hydraulic stations, surface thermoelectric mats for soil heating, for example, TM – 800 (Russia).

The aim of development is to accelerate and reduce the cost of mining and construction work in frozen ground, associated with the need its thaw. At present, three methods for thawing of frozen soil during these operations are commonly used. The first one is to lay fire from firewood at the place where it is necessary to thaw and excavate the ground, and usually the first row of firewood does not burn and forms a kind of thermal insulation of frozen ground from the heat generated during the burning of firewood. The second way is to burn charcoal or other combustible materials on iron sheets at the place where thawing should be performed. The third one is to heat permafrost with a flame of special lamps for liquid fuel [10].

A review of patents and inventor's certificates made it possible to formulate a list of analogues of the device being developed. A back-draft portable furnace with air-cooled tubular grate is the closest analogue. In order to heat the soil, the casing of furnace is made without backstone in ash pan and has a number of flue gas vents along its edge. A pipeline for input of additional hot air into the under-the-head space is connected to the collector adjacent to the grate in addition to the pipeline for usual distribution of air above the fuel layer to improve the combustion conditions and increase the temperature of gases flowing around the soil. This device has several disadvantages, namely the low efficiency of solid fuel combustion and the probability of absence of the required draft and creation of the so-called “back draft” for sufficient temperature pressure of flue gases in the working area of furnace, as well as a small heating area. Further research is aimed at solving these drawbacks.

3 Description of the unit construction

When designing modern heat-generating devices, the following requirements should be met: it should provide a simple and economical transportation of heat to the work surface; have the most rational scheme of fuel supply and ash removal; have the best working conditions for operating personnel; be highly economical and safe to use.

The unit must be equipped with a primary air regulator. The design must ensure that during its operation, neither residues of combustion products nor unburned fuel can disrupt motion or shut-down of the air supply regulator. It should also be able to completely clean the combustion path. The minimum width of the combustion path should be 30 mm [11].

The purpose of the device being developed is to improve the quality, reliability and efficiency of devices used to heat working fluids, improve the methods of surface heating and warming of frozen soil, concrete, road pavement by radiation-convective method, with minimum energy and time requirements, taking into account the environmental safety requirements with emissions of exhaust gases into the air, the detection and study of defects in the working bodies.

The following solutions are proposed: the furnace body is formed by an iron frame with grates. The grates are covered by a double vault. The air initially enters the space between the sheets 1, through the nozzles of grate 2 passing through the regulating flow damper 3 enters the space 4, through the holes is distributed evenly over the surface of the furnace. Air is pumped by a manual fan, enters the furnace and the under-grate space for combustion of exhaust gases. The combustion products through the grates go to ash pan 6 and, meeting a soil segment, make thawing not only by hot gases, but also by the radiant heat of the burning fuel.

Fuel (firewood) is loaded through the upper door 7 (see Fig. 2), which is tightly closed during operation. Furnace can be additionally equipped by adjustable manifolds and channels to increase the path of the exhaust combustion products.

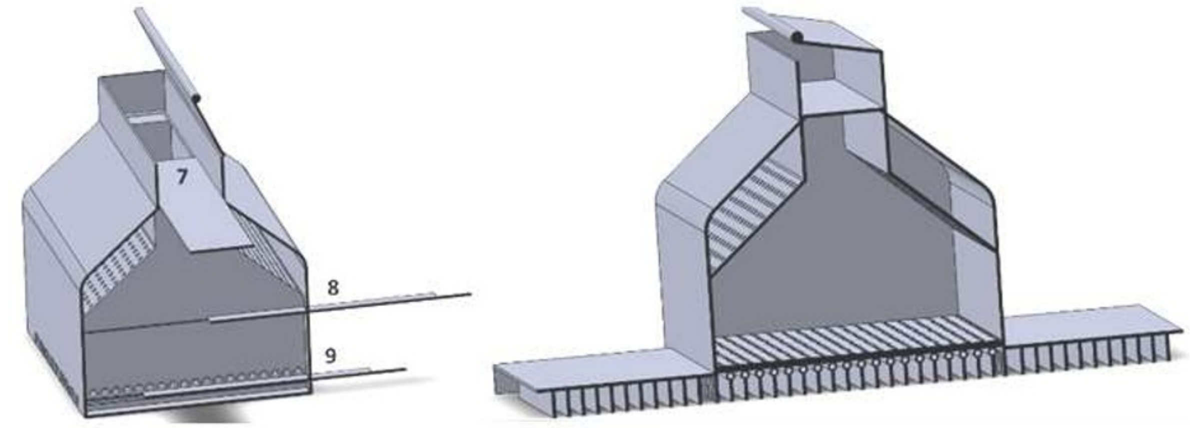

Fig. 2. Three-dimensional space model of a solid fuel furnace with back draft.

This design has the following advantages over its analogues:

- The injected air is preheated from the walls of combustion chamber, therewith cooling the grate and reducing furnace wear, while increasing the efficiency of fuel combustion;
- The area of soil heating can be increased due to adjustable manifolds;
- Solid fuel is the best option in cold conditions and does not require preliminary preparation;
- Before feeding into the combustion chamber, the wood is heated by the walls of combustion chamber (preliminary drying takes place).

4 Experimental data

As a rule the modelling process is iterative, which involves at each iteration step the refinement of solutions made at previous steps of model development. Mathematical modelling has several advantages over real experiment, including profitability (saving the resources of real system); the possibility of modelling hypothetical (not realized in nature) objects; the possibility of implementing dangerous or difficult to reproduce in nature modes, as well as the universality of hardware and software of the work performed.

In mathematical modelling, the Stefan problem was used, which is solved as a system of heat equations taking into account the phase transition.

The problem statement is as follows: the soil has the initial temperature T_{in}, and it is frozen. The phase transition temperature T_{ph} is higher than T_{in}. On the soil surface x=0 at initial time t=0, a constant temperature T_0 is established abruptly and maintained above the freezing temperature. The melt layer that appears at the surface increases with time. A front is established, the motion of which should be determined, as well as temperatures in thawed and frozen zones.

The coordinate of front freezing is denoted as x_1, temperature in the melt layer $0 \le x \le x_1$ is denoted as $T_1(x,t)$, $T_2(x,t)$ is the temperature in not warmed area $x_1 \le x \le \infty$. Consequently, the problem of warming up the soil is considered as the problem of conjugating temperature fields on a warming front that moves, so finally we get a system of equations of thermal conductivity.

$$\left.\begin{aligned} \frac{\partial T_1}{\partial t} &= a_1 \frac{\partial^2 T_1}{\partial x^2}, 0 \le x \le x_1 \\ \frac{\partial T_2}{\partial t} &= a_1 \frac{\partial^2 T_2}{\partial x^2}, x_1 \le x \le \infty \end{aligned}\right\}, \qquad (1)$$

where a_1 is the coefficient of thermal diffusivity in the thawed zone and a_2 is the coefficient of thermal diffusivity in the frozen zone with initial conditions

$$T_2(x,0) = T_{in}, \qquad (2)$$

$$T_1(0,t) = T_0 > T_{ph}, \qquad (3)$$

$$T_1\big|_{x_1} = T_2\big|_{x_2} = T_{ph} = const, \qquad (4)$$

To simplify the solution, we take $T_{ph} = 0$, thereby switching to the Celsius scale. One can change the zero point according to the requirements.

The front moves with a predetermined speed, therefore, in addition to the boundary conditions (4) for the heat equations, it is necessary to set one more parameter that determines the front speed. Assume that for some time dt the front moves a distance dx_1. At the same time, a mass of water equal to $rSdx_1$ is melt and the amount of heat $LrSdx_1$, is absorbed, where S is the front surface area, L is the specific heat of phase transition, r is the mass of water per unit volume of soil. According to the law of conservation of energy this amount of heat must be equal to the difference in heat amount passing from the frozen and thawed areas through the front:

$$\left[-\lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x_2} + \lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x_1}\right] Sdt = L\rho Sdx_1, \qquad (5)$$

or

$$\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x_1} - \lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x_2} = L\rho \frac{dx_1}{dt}, \quad (6)$$

This condition is called the Stefan condition at the front of phase transition. Solution of equations (1) should be searched in the form:

$$T_1 = A_1 + B_1 erf\left(\frac{x}{2\sqrt{a_1 t}}\right); \qquad T_2 = A_2 + B_2 erf\left(\frac{x}{2\sqrt{a_2 t}}\right), \quad (7)$$

where A_1, A_2, B_1, B_2 are the unknown constants, which are determined from the boundary and initial conditions.

During problem solution, a formula was obtained that shows the law of defrosting front motion.

$$x_1 = \beta\sqrt{t}, \quad (8)$$

where β is the unknown constant at this point, which is further found from the final transcendental equation.

$$\frac{\lambda_1 T_0 e^{-\frac{\beta^2}{4\alpha_1}}}{\sqrt{a_1}\, erf\left(\frac{\beta}{2\sqrt{a_1}}\right)} + \frac{\lambda_2 T_{н} e^{-\frac{\beta^2}{4\alpha_2}}}{\sqrt{a_2}\, erfc\left(\frac{\beta}{2\sqrt{a_2}}\right)} = L\rho\beta\frac{\sqrt{\pi}}{2}, \quad (9)$$

Thus, if thermophysical parameters of substance $\lambda_1, \lambda_2, a_1, a_2, L, r,$ and boundary and initial temperatures T_0 and T_{in} are given, then constant β, as well as constants A_1, A_2, B_1, B_2 in further calculation are uniquely determined.

Analyzing the motion of phase transition boundary as a function of time, we can conclude that the soil density affects the heating time, the higher the density, the longer time thawing will take. Using the formulas presented above, a graph of temperature distribution from surface in 5..10..20 minutes was constructed, which gives us a visual representation of the process taking place underground.

Further, the results of mathematical modelling are presented in plots.

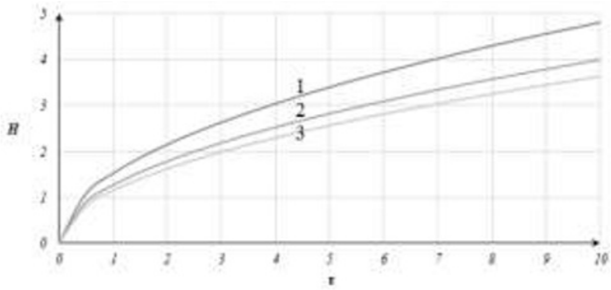

Fig. 3. Motion of phase transition boundary (H, cm) as a function of time (τ, min).

Fig. 3 shows plant layer, peat with ρ=1200 kg/m^3 (1); sands, sandy loam, loam ρ=1750 kg/m^3 (2); soil with a particle size of more than 80 mm (3), with boulders content up to 30% ρ=2100 kg/m^3.

It was determined that performance of a power unit depends on many factors: the type, structure of frozen soil and its thermo-physical properties, climatic conditions and the nature of soil surface, the volume of thawed soil and the frequency of its removal from the pit, etc. Regarding the latter factor, it is worth to note that experimental studies by the experimental unit, conducted in field conditions, showed that the character of removal of the thawed part has a strong influence on the speed of thawing of frozen soil. For 1.3 kW power expenditures and a thawing area of 85·10^{-3} m^2 of bulk sandy soil, generalizing experimental dependences of the time-varying depth of artificial thawing of the soil were obtained.

The speed and, accordingly, the depth of thawing depends on the conditions for removal of thawed soil. With constant removal of soil (every 5 min), the depth of thawing is 3 times greater than for thawing without removing it. With periodic (every 15 min) removal of

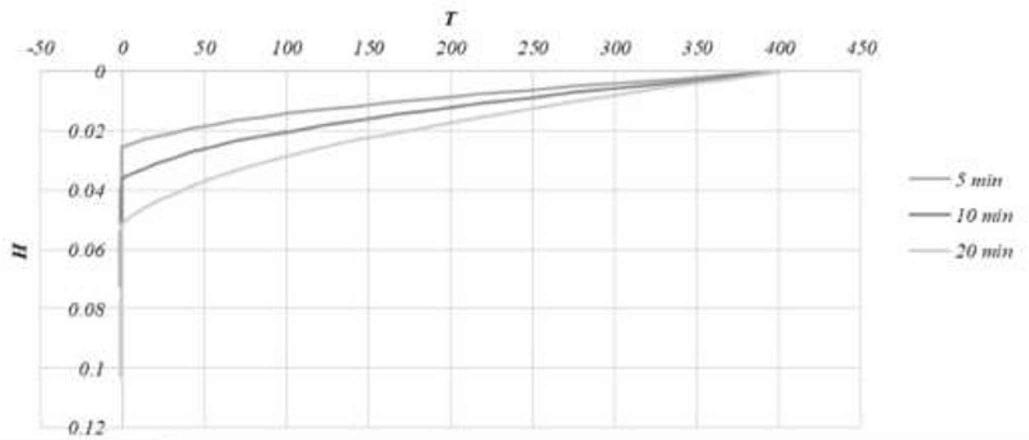

Fig. 4. Temperature distribution after 10 minutes of unit operation (*T*, ◦C), as a function of distance to surface *H*, m.

soil, the depth of thawing is 2 times greater than for thawing without soil removal, which was taken into account when developing the technology for the unit operation.

5 Conclusions

It can be said that the presented unit is suitable for use during works related to the development of frozen soil, heating of building materials and heating of complex building structures to determine defects by non-destructive testing.

In comparison with the existing technical means, the unit being developed is efficient and commercially viable.

In addition, the main features of the proposed unit are highlighted:

- Its construction and design have no analogues in the modern market of technical equipment for repair and construction works;
- It has the minimum time for warming up frozen soil compared to the existing units;
- Low specific energy consumption of the unit together with the combined heat transfer method ensure its high efficiency;
- The mobility and compactness of the unit allows its transporting in a truck and carrying out work by a team of two people under lack of space of the urban landscape;
- The flexibility of regulating the heat output of the unit ensures its use for thawing building materials and heating building structures for any purpose;
- Energy-efficient combination of unit elements and a thermo-insulated housing can provide repair and construction work in any climatic conditions.

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