DEVELOPMENT OF A COMPUTER CODE TO PREDICT A VENTILATION REQUIREMENT FOR AN UNDERGROUND RADIOACTIVE WASTE STORAGE TANK

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Abstract

Computer code, WTVFE (Waste Tank Ventilation Flow Evaluation), has been developed to evaluate the ventilation requirement for an underground storage tank for radioactive waste. Heat generated by the radioactive waste and mixing pumps in the tank is removed mainly through the ventilation system. The heat removal process by the ventilation system includes the evaporation of water from the waste and the heat transfer by natural convection from the waste surface. Also, a portion of the heat will be removed through the soil and the air circulating through the gap between the primary and secondary tanks. The heat loss caused by evaporation is modeled based on recent evaporation test results by the Westinghouse Hanford Company using a simulated small scale waste tank. Other heat transfer phenomena are evaluated based on well established conduction and convection heat transfer relationships.

I. Introduction

The ventilation system has been used as the main method of removing heat from the underground tank that stores heat-generating radioactive waste materials on the Hanford Site. The ventilation system can remove a large amount of heat from the waste tank by introducing cold and dry air into the tank vapor space and removing hot and humid air. The ventilation air removes a major portion of the heat from the tank by carrying away water vapor evaporated from the waste surface. Also, the heat is removed from the waste surface to the ventilation air by the natural convection in the vapor space. In addition to the ventilation air, a small portion of the heat will be removed by air circulating between the primary and secondary tanks (annulus flow). The tank will lose heat through the soil if the temperature of the tank is higher than the temperature of the surrounding soil. An evaluation of the required ventilation flow to remove the heat from the waste tank is an important design parameter for the design of a new tank.

Waters[1] developed a simple code to predict the ventilation requirement based on the evaporation rate equation developed by Boelter et al[2]. In this code, other heat transfer phenomena such as the natural convection have not been evaluated properly. Recently, Crea[3] at Westinghouse Hanford Company has performed an experiment measuring the evaporation rate from a 12-ft (3.66-m) diameter simulated waste tank to improve the Boelter equation. Based on these experimental results, computer code WTVFE has been developed to predict the ventilation flow conditions for a waste tank containing heat-generating elements. Also, other heat transfer phenomena have been properly treated in this new code.

II. Description of Analysis Methods

This section discusses the analysis methods used in code WTVFE for various heat removal modes such as evaporation, natural convection, conduction through the soil, and heat removal by the annulus flow. The analysis methods are based on steady-state conditions with well mixed waste.

1. Evaluation of Evaporation Rate from the Waste

Since water has a large latent heat, a small amount of water evaporation from the waste into the ventilation system will remove a significant amount of the heat from the tank. The water vapor pressure in the ventilation outlet depends on the equilibrium between the amount of water vapor transferred from the waste surface to the bulk air space above the waste and the amount of vapor taken away by the ventilation system. In this evaluation, it is assumed that the bulk air inside the tank is well-mixed and that the outlet condition of the ventilation air is the same as that of the bulk air inside of the tank. Boelter et al[2] have developed the following equation to predict the amount of the water vapor transferred from the pure water surface to the bulk air based on the experimental data.

$$W = 0.00129A(P_i - P_b)^{1.22} \quad (1)$$

where:

- W -- amount of water vapor transferred (lb/hr)
- A -- surface area (ft^2)
- P_i -- waste surface water vapor pressure (mm Hg)
- P_b -- bulk phase water vapor pressure (mm Hg)

The validity of applying the Boelter equation to a large tank has been questioned, since Boelter et al developed the empirical equation based on experimental data using a small pan. To confirm the Boelter equation for a large tank like the radioactive storage tanks at Hanford, an experiment was performed by Westinghouse Hanford Company[3] to measure the evaporation rate from a 12-ft (3.66-m) diameter tank. The comparison between the experimental results and the predictions by the Boelter equation shows that the predictions by the Boelter equation are an average of 2.9% lower than the experimental data. In the code, Boelter's equation has been used for the calculation of the evaporation rate with this adjustment. Table 1 summarizes the comparisons between the experimental data and the predictions by the original and improved Boelter's equation.

Table 1 Comparison between Westinghouse Experimental Data and Predictions for Water Loss.

Test Run No	Experimental Data ($lb/hr*ft^2$)	Prediction Boelter ($lb/hr*ft^2$)	Error (%)	Prediction Modified ($lb/hr*ft^2$)	Error (%)
1	1.2	1.19	-0.8	1.23	2.5
2	14.75	15.13	2.6	15.5	5.1
3	29.03	25.38	-12.6	25.9	-10.8
4	12.73	12.47	-2.0	12.79	0.5
5	23.98	22.86	-4.7	23.35	-2.6
7	30.25	27.16	-10.2	27.69	-8.5
6	9.78	8.92	-8.8	9.14	-6.5
8	23.96	21.9	-8.6	22.39	-6.6
11	25.79	22.06	-14.5	22.54	-12.6
12	3.52	2.98	-15.3	3.05	-13.4
10-10R	8.71	8.5	-2.4	8.71	0.0
17	2.58	2.74	6.2	2.81	8.9
20	12.66	13.39	5.8	13.68	8.1
5R	23.43	23.8	1.6	24.3	3.7
6R	8.48	9.02	6.4	9.25	9.1
9	14.57	16.0	9.8	16.37	12.4
21	4.92	4.55	-7.5	4.67	-5.1
13	0.71	0.69	-2.8	0.72	1.4
22	1.53	1.44	-5.9	1.49	-2.6

The inlet flow rate of the ventilation air required to remove the water vapor transferred from the waste surface shown in equation (1) is equal to:

$$V_a = \left(\frac{760}{60\rho(760-P_n)}\right)\left(\frac{1.6W}{\frac{P_b}{(760-P_b)} - \frac{P_n}{(760-P_n)}}\right) \qquad (2)$$

where:

V_a -- inlet ventilation air flow rate (SCFM)
P_n -- inlet air water vapor pressure (mm Hg)
ρ -- air density (lb/ft^3)

Since the waste contains chemicals, the vapor pressure is lower than pure water. The code has an arrangement to input the factor representing the vapor pressure suppression due to chemicals in the waste.

2. Evaluation of Ventilation Exit Air Temperature

The ventilation air removes heat from the waste by increasing the air temperature while the air is passing through the tank. To evaluate this method of heat removal, the temperature of the ventilation exit air has to be evaluated accurately. As stated previously, the exit conditions of the ventilation air is assumed to be the same as that of the bulk air inside of the tank. The temperature of the ventilation exit air is dependent on the heat transfer rate from the waste surface to the bulk air space above the waste and the ventilation air flow rate. The heat is transferred to the bulk air from the waste surface by the natural convection caused by the density difference between the bulk phase and the interface at the waste. This density difference is caused by the temperature and water vapor pressure differences.

The relationships between the Nusselt number (Nu) and the Rayleigh number (Ra) have been established for laminar and turbulent natural convection[4]. The heat transfer coefficient from the waste surface to the bulk phase can be calculated from these relationships. The Nu and Ra numbers are defined as

$$Nu = \frac{h}{Lk} \qquad (3)$$

where:
- h -- heat transfer coefficient (Btu/hr*F*ft^2)
- k -- conductivity (Btu/hr*F*ft)
- L -- characteristic length (ft)

$$Ra = \frac{g\Delta\rho L^3 \rho_f Cp_f}{\mu_f k_f} \qquad (4)$$

where:
- g -- acceleration of gravity (ft/hr^2)
- $\Delta\rho$ -- density gradient ($=(\rho_b-\rho_i)/\rho_i$)
- Cp -- specific heat (Btu/lb*F)
- μ -- viscosity (lb/ft*hr)
- subscript i -- interface
  - b -- bulk phase
  - f -- film

The relationship between the Nu and Ra number for the laminar natural convection ($Ra < 10^8$) is

$$Nu=0.56Ra^{1/4} \qquad (5)$$

and the relationship for the turbulent natural convection ($Ra > 10^8$) is

$$Nu=0.13Ra^{1/3} \qquad (6)$$

The exit temperature of the ventilation air can be evaluated from the energy balance equation using the heat transfer coefficient obtained by either equation (5) or (6).

$$60V_a\rho Cp_a(T_b-T_n) + Cl = 1.5hA(T_i-T_b) + (Cp_sW+Cp_aW_{1c})(T_i-T_b) \qquad (7)$$

where:

- T -- temperature (F)
- Cl -- heat loss through soil (Btu/hr)
- W_{1c} -- air flow rate trough air lift circulation (lb/hr)
- subscript n -- inlet
  - a -- air
  - s -- water vapor

The heat transfer surface, A in equation (7), is increased by 50% to account for the side wall of the tank above the waste. This surface increase minimizes the exit temperature differences between predicted values and experimental data.

Also, the code prediction for the exit temperature of ventilation air has been compared to the Westinghouse experimental data[3]. The results show that the predicted values are an average 1.2% lower than experimental ones. This difference has been factored into the code. In this comparison, a few experimental data have been disregarded since its values are so obviously erroneous. Table 2 summarizes the

Table 2. Comparison between Westinghouse Experimental Data and Predictions for Exit Air Temperature

Test Run No	Experimental Data(F)	Prediction Theory(F)	Error (%)	Prediction Modified(F)	Error (%)
1	98.8	96.0	-2.8	96.8	-2.0
2	170.1	166.8	-1.9	167.5	-1.5
3	154.4	149.0	-3.5	149.8	-3.0
4	171.7	168.4	-1.9	169.0	-1.6
5	167.2	168.8	1.0	170.4	1.9
7	163.6	159.3	-2.6	160.9	-1.7
6*	167.3	180.6	-	182.3	-
8*	172.2	182.4	-	184.2	-
11	172.2	168.6	-2.1	170.3	-1.1
12	126.2	123.0	-2.5	124.1	-1.7
10-10R	155.3	154.7	-0.4	156.1	0.5
17	141.1	143.5	1.7	144.8	2.6
20	154.2	147.8	-4.2	149.2	-3.2
5R	170.9	169.5	-0.8	171.2	0.2
6R	174.3	182.2	4.5	183.9	5.5
9*	155.3	172.6	-	174.3	-
21	140.1	138.9	-0.9	140.1	0.0
13	95.6	91.8	-4.0	92.6	-3.1
22	127.4	129.0	1.3	130.1	2.1

* These runs are not used for the comparison.

comparisons between the experimental data and the predictions by the original and improved code calculations. If the exit water vapor pressure calculated in the previous section is higher than the saturation vapor pressure at the exit air temperature calculated in this section, the code will evaluate the exit air temperature where the exit vapor pressure matches with the saturation pressure. In this calculation, it is assumed that the heat that increases the exit air temperature to the saturation temperature comes from the condensation of the water vapor.

3. Evaluation of Heat Loss through the Soil

Since the waste tanks on the Hanford Site are underground, heat loss from the tanks to the soil will occur when the waste temperature is higher than that of the surrounding soil. Because the surrounding soil has a large heat capacity and the amount of heat generated by the waste in the tank is relatively small, it will take a long time to reach a steady state during the operation. In the code, it is assumed that there is a water table with a constant temperature of 55°F (12.8°C) below 200-ft (60.96-m) from the tank bottom and the surrounding soil has reached the steady state temperature as suggested in the thermal analyses of the MWTF(Multi-Function Waste Tank Facility) design[5]. Also, there is a steady state heat loss through the soil covering the top of the tank to the outside air.

A simplified model developed for a disc heat source stored in the infinite medium[6] was used as the basis for the calculation of heat loss from the tank through the soil to the water table. The tank is assumed to be a disk, since the tank height is small compared with the distance from the tank to the water table and the upper portion of tank will loose heat to the outside air. Furthermore, the pads installed under the tank bottom, such as the concrete and insulating pads with annulus air distribution channels, are ignored since the conduction resistance through 200- ft (60.96-m) of soil is dominant compared with the resistance through these pads.

$$Q_{cb} = \left(\frac{4.45D}{1 - \frac{D}{1-5.67z}} \right) k_z (T_t - T_w) \tag{8}$$

where:

Q_{cb} -- heat loss to water table (Btu/hr)
D -- tank diameter (ft)
z -- distance from tank bottom to water table (ft)
subscript t -- tank
w -- water table
z -- soil

The conductivity of the soil is estimated to be 0.35 Btu/F*hr*ft (0.606 W/m*K) in the code[5].

The heat loss from the top of the tank to the outside air was evaluated assuming that the top surface of the tank is a flat circle and the heat transfer path in the soil is limited to the cylindrical area above the tank. This is an acceptable approach since the depth from the ground surface to the tank is not generally deep. Also, a factor is assigned to adjust possible error due to this simplification as shown in the following equation.

$$Q_{ct} = F\pi D^2 \frac{1}{h_a + \frac{d_s}{k_s} + \frac{d_c}{k_c}} \qquad (9)$$

where:

Q_{ct} -- heat loss to outside air (Btu/lb)
F -- factor to adjust the error
d -- Thickness (ft)
subscript c -- concrete

The heat transfer coefficient from the ground to the air is assigned to be 0.5 Btu/F*hr*ft^2 (2.837 W/m^2*K) and the conductivity of the concrete to be 0.6 Btu/F*hr*ft (1.038 W/m*K) in the code.

If the tank top surface is not flat, it is recommended to use the average depth based on the area. The factor assigned to accommodate any possible error was determined to be 1.12 comparing the code predictions with the calculation results using a sophisticated finite element code[7] for the design of the MWTF tank[5]. The comparisons between the finite element code calculations and the predictions with and without a factor by equation (9) are summarized in Table 3. Since the factor in equation (9) was determined based on the comparison to the analysis data for only the MWTF design, a large amount of error is possible in applying this factor to other configurations. However, an error in the conduction loss calculation will not significantly affect the evaluation of the ventilation flow rate in most cases since the conduction loss through the soil is very small compared with the other losses.

Table 3. Comparison between Finite Element Calculations and Predictions for Heat Loss through Soil

Waste Temperature (F)	Out side Air Temperature (F)	Finite Element Prediction (Btu/hr)	The Code Prediction (Btu/hr)	Error (%)
187	77	33000	31166	-5.6
118	77	12000	13539	12.8
109	77	10000	10963	9.6
104	77	9000	9757	8.4
98	77	7000	8136	16.2
93	53	12000	10267	-14.4
88	53	9000	8771	-2.5
69	53	4000	3928	-1.8
64	53	3000	2577	-14.1

4. Evaluation of Heat Loss to Annulus Air Flow

Most of the waste tanks designed to store radioactive nuclear waste have a secondary containment. Air is circulated through the gap between the primary tank and the secondary tank in to detect any radioactive waste leak from the primary tank. This circulating air is called the annulus air flow and removes heat from the tank. The overall heat transfer coefficient from the waste to the annulus air flow consists of the resistance in the waste side, tank wall, and air side heat transfer coefficients. An arbitrarily high heat transfer coefficient of 10 Btu/F*hr*ft^2 (56.74 W/m^2*K) has been assigned for the waste side since the waste is assumed to be well mixed.

For the air side, the heat transfer coefficient[8] based on natural convection was used when the air flow was not turbulent (Reynolds number is less than 10^4).

$$h_a = 0.19 \ (\Delta T)^{1/3} \qquad (10)$$

where:
ΔT -- Temperature difference (F)

Since the temperature difference is not uniform (large at the bottom of the tank and small at the top of the tank), the logarithmic mean temperature difference is used for the calculation. When the air flow is turbulent, the heat transfer coefficient is evaluated based on forced convection[9].

$$h_a = 0.023 \ Re^{0.8} Pr^{0.4} \ k_a/Gp \qquad (11)$$

where:
Re -- Reynolds number
Pr -- Prandtl number
Gp -- gap distance (ft)

In this equation, properties of the air are evaluated at 100°F (37.8°C).

For the overall heat transfer calculation, it is assumed that air is uniformly distributed throughout the annulus and that 30% of the tank bottom area is in contact with the annulus air. When the annulus air temperature is higher than waste temperature, it is assumed in the code that there is no heat transfer between the annulus air and the waste.

5. Consideration on Air Lift Circulation Air

Some of the radioactive waste storage tanks on the Hanford Site have an air lift circulation system to mix the waste during storage. In the air lift circulation system, air is introduced into the waste and passes through it as bubbles. Since air from the air lift circulation system is introduced into the waste, it is assumed in the code that the air temperature leaving the waste is the same as the waste temperature and that the water vapor pressure in the air is the same as the saturation vapor pressure for the waste at the surface. When air from the air lift circulation system mixes with the ventilation air, proper material and energy balance equations are solved to account for the high air temperature and vapor pressure from the air lift circulation system.

III. Description of Computer Code

This section presents a brief description of computer code WTVFE. The code is written in Q-Basic language and a detailed description on how to use the code is in the user's manual section of reference 10.

The code requires the ventilation air inlet conditions, the annulus flow rate, tank geometry and the vapor suppression factor for the waste as input data. Also, it requires the waste temperature and the heat generation rate as input data. First, the code calculates the heat removal rate by the conduction through the soil and annulus air flow. Then, it calculates the amount of water to be vaporized in order to remove the rest of the heat, assuming that heat removal due to the ventilation air temperature rise is negligible. The required vaporization rate is converted to the required ventilation flow rate using equation (2). Based on the required ventilation flow rate and the outlet temperature to be calculated later, heat removal by the ventilation air temperature rise will be calculated and the required ventilation flow rate recalculated. This iteration continues until the previous value of the ventilation flow rate matches the recalculated value within 0.5% of error.

After the iteration of the ventilation flow rate, the iteration of the ventilation air exit temperature will be performed. First, the temperature of the exit air is assumed to be 20°F (11°C) lower than the waste temperature. Using this assumed exit temperature, the Ra number and heat transfer coefficient are calculated. Then, the temperature of the exit air is calculated using equation (7). If the difference between the calculated temperature and the assumed temperature of the exit air is larger than 0.05°F (0.03°C), the exit temperature will be reassigned based on the previously assumed and calculated values. This iteration continues until the difference becomes less than 0.05°F (0.03°C).

After the exit air temperature is converged properly, the code will return to the iteration of ventilation air flow rate again with the newly calculated exit air temperature. Iteration of the ventilation air flow rate and exit air temperature will be repeated until the differences between the previous values and the recalculated values of both variables are within the desired limits.

IV. Conclusions

Computer code, WTVFE, has been developed successfully to predict the requirement of the ventilation air flow rate for an underground storage tank for heat-generating radioactive materials.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by ICF Kaiser Hanford Company under contract number DE-AC06-87RL-10900.

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DISCUSSION

BERGMAN: We heard this morning from Louis Kovach about potential accidents in some of the tank farms, e.g., explosions, filter burstings, things like that. Can you tell us something from your experience that you have actually observed; cracks, things of that nature?

DALPIAZ: No, I don't have any actual experiences I could use to answer your question.

PORCO: I will address this to speakers from Hanford. Based on your experience with tank farm ventilation, what do you see as the biggest need for product development? I guess the best way to phrase it is, is there a lack in the industry for a product that would serve your needs or assist you in treatment? Is everything that you need available in the market today?

RICE: The thing that comes to my mind right away as the biggest concern at Hanford, is flammable gas issues. Control of particulates is really not a problem and has never been a problem as far as I know. Sometimes the filters have a rough life and they may need rapid change-out, but they have never really been a big deal. But now the flammable gas issue is the real problem. What we are faced with are tanks that generate flammable gases in the waste that can build a pressure under the crust and then suddenly overturn the contents and make a large release to the environment. There have been occasions of this occurring. There is one tank in particular that has equipment in it, a mixer pump, to prevent gas build up by keeping the contents agitated. This prevents episodic releases of gas, by allowing continuous average releases. In the paper I presented we discussed a cleanable mist eliminator that is taking out particles. We may find out that it loads up quickly or that there is some problem with washing it. That is why we studied the prototype. We hope, based on the prototype test, that it will turn out to be okay.

BERGMAN: I forgot the exact details, but Russia had some tanks out by the Urals that had minor mishaps. And I think they had, as a consequence, several hundred miles of uninhabitable area. I am sure this is well known to your people. I was not quite satisfied with your response to my earlier question as we have an inconsistency between what Louis Kovach said this morning and what you are saying. And I would like to find out who is telling the truth.

BELLAMY: I think Dr. Kovach was indicating a little different opinion this morning . You are welcome to comment further if you want. I don't think it's a question of who is telling the truth and I do not think we should go further with that thought. The way I interpreted Mr. Porco's question was that, as a representative of the industry, if there is some piece of equipment that would help to control radioactive releases from the Hanford facility, please speak up and maybe we can take care of it. The answer I heard was that, there really is nothing that would basically solve all our problems.

RICE: I think there is really a lot to the idea that the codes and standards that we are forced to use in the processing industry are related to the nuclear power plant industry. They really do not line up very well with the real problems that we are trying to solve. We have been getting by, but if there were a set of codes and standards designed for processing and reprocessing, maybe some new equipment would come out to meet those codes. But right now, we have only N-509 and we build HEPA filter systems to that standard.