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THERMAL ANALYSIS OF COMPRESSIBLE CO_2 FLOW FOR MAJOR EQUIPMENT OF FIRE DETECTION SYSTEM

Michael Y. Zhang, Wen-Ching Lee and John F. Keener

Lockheed Martin Space Operations
2400 NASA Road 1
Houston, Texas 77058

Frederick D. Smith

NASA Lyndon B. Johnson Space Center
2101 NASA Road 1
Houston, Texas 77058

Prepared for Presentation at the 2001 AICHE Spring National Meeting
Houston, TX, April 22 - 26

April 2001

Abstract

A thermal analysis of the compressible CO_2 flow for the Portable Fire Extinguisher (PFE) system has been performed. The purpose of this analysis is to determine the discharged CO_2 mass from the PFE tank through the Temporary Sleep Station (TeSS) nozzle in reflecting to the latest design of the extended nozzle, and to evaluate the thermal issues associated to the latest nozzle configuration. A SINDA/FLUINT model has been developed for this analysis. The model includes the PFE tank and the TeSS nozzle, and both have initial temperature of 72 ^{o}F. In order to investigate the thermal effect on the nozzle due to discharging CO_2, the PFE TeSS nozzle pipe has been divided into three segments. This model also includes heat transfer predictions for PFE tank inner and outer wall surfaces. The simulation results show that the CO_2 discharge rates have fulfilled the minimum flow requirements that the PFE system discharges 3.0 lbm CO_2 in 10 seconds and 5.5 lbm of CO_2 in 45 seconds during its operation. At 45 seconds, the PFE tank wall temperature is 63 ^{o}F, and the TeSS nozzle cover wall temperatures for the three segments are 47 ^{o}F, 53 ^{o}F and 37 ^{o}F, respectively. Thermal insulation for personal protection is used for the first two segments of the TeSS nozzle. The simulation results also indicate that at 50 seconds, the remaining CO_2 in the tank may be near the triple point (gas, liquid and solid) state and, therefore, restricts the flow.

1.0 INTRODUCTION

The Portable Fire Extinguisher (PFE) system has been designed by ARDE Inc. for space application and has passed the qualification test[1] in October 1995. The PFE system has been employed as the Fire Fighting Equipment in the International Space Station's Temporary Sleep Station (TeSS). The purpose of this analysis is to determine the discharged CO_2 mass from the PFE tank through the TeSS nozzle in reflecting to the latest design of the extended nozzle, and to evaluate the thermal issues associated to the latest nozzle configuration. This investigation is part of the Temporary Sleep Station Ventilation Analysis.

2.0 PORTABLE FIRE EXTINGUISHER SYSTEM

The PFE system consists of an 847 cubic inches CO_2 tank, an on/off trigger, a pressure coupler, a tubular nozzle assembly and a conical tube nozzle assembly. The conical tube nozzle assembly is designed to extinguish fire in open areas while the tabular nozzle assembly is designed for enclosed areas such as equipment racks. The original nozzle of the PFE system has been modified and extended from its original length of 12.8 inches to 18.3 inches. The extended nozzle has a 0.527 inches diameter and nine small jet holes (0.062 inches diameter each) at the nozzle tip. The compressed CO_2 gas (860 psia and 72 ^{o}F) is discharged from the PFE tank through the TeSS nozzle. In addition, a 45-degree bend and a cover (thermal insulation) on the nozzle have been included in the design. This latest nozzle design is indicated as the TeSS nozzle and a sketch is shown in Figure 1.

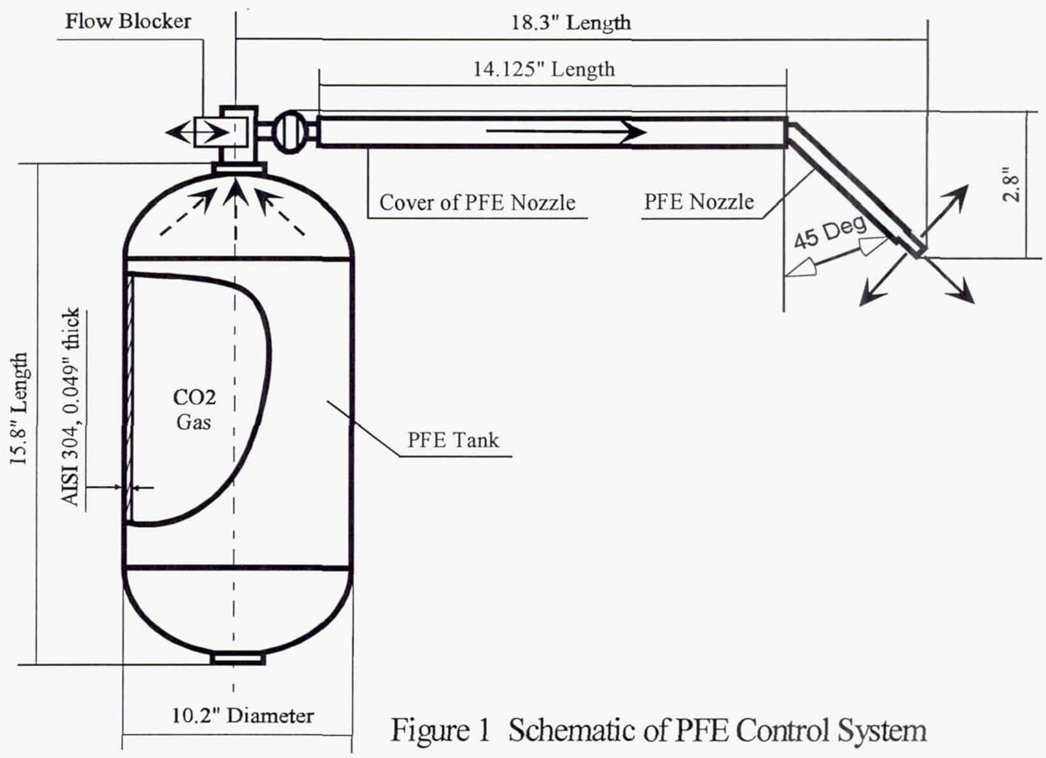

Figure 1 Schematic of PFE Control System

3.0 DESCRIPTION OF SINDA/FLUINT MODEL

3.1 The SINDA/FLUINT Model Set Up and Verification

To conduct the thermal analysis of the compressible CO_2 flow for the portable fire extinguisher system, a SINDA/FLUINT model was developed using X-38/Shuttle GN_2 tank modeling techniques[2-4] with relevant geometry and material properties data taken from the portable fire extinguisher tank and TeSS nozzle. This model includes the PFE tank and the PFE TeSS nozzle. In order to investigate the thermal effect on the nozzle due to discharging CO_2, the PFE TeSS nozzle pipe has been divided into three segments. This model also includes heat transfer predictions for tank inner and outer wall surfaces. This model determines the pressure, temperature, and mass distribution for the tank. It also calculates temperature distribution and flow rate through the nozzle segments. A schematic of the SINDA/FLUINT model is shown in Figure 2. It includes components used in the model as well as the flow paths for CO_2.

In Figure 2, the TANK Node 100 simulates the PFE tank volume. An active control valve 105 is connected to the tank by a STUBE connector 115 and JUNC node 10 to control the CO_2 flow. To simulate heat transfer from the tank wall to the CO_2 gas, tank inner wall node 101, outer wall node 9999, and ambient air node 9990 are created in the thermal submodel. Two conductors 1001 and 1002 are established between these nodes, and the heat transfer tie 1111 is connected between the inner wall and CO_2 gas. Similarly, to simulate heat transfer from the PFE nozzle wall to CO_2 gas, the nozzle inner wall nodes 201, 202, and 203, the outer wall nodes 301, 302, and 303, and ambient air nodes 9001, 9002, and 9003 are considered in the thermal submodel. Six conductors 2001, 2002, 2003, 3001, 3002, and 3003 are established between the nodes, and the heat transfer ties 211, 212 and 213 are also connected between the inner wall and CO_2 gas for those three segments, respectively. JUNC 45 represents the tip of the nozzle, which has nine small jet holes for CO_2 gas spraying.

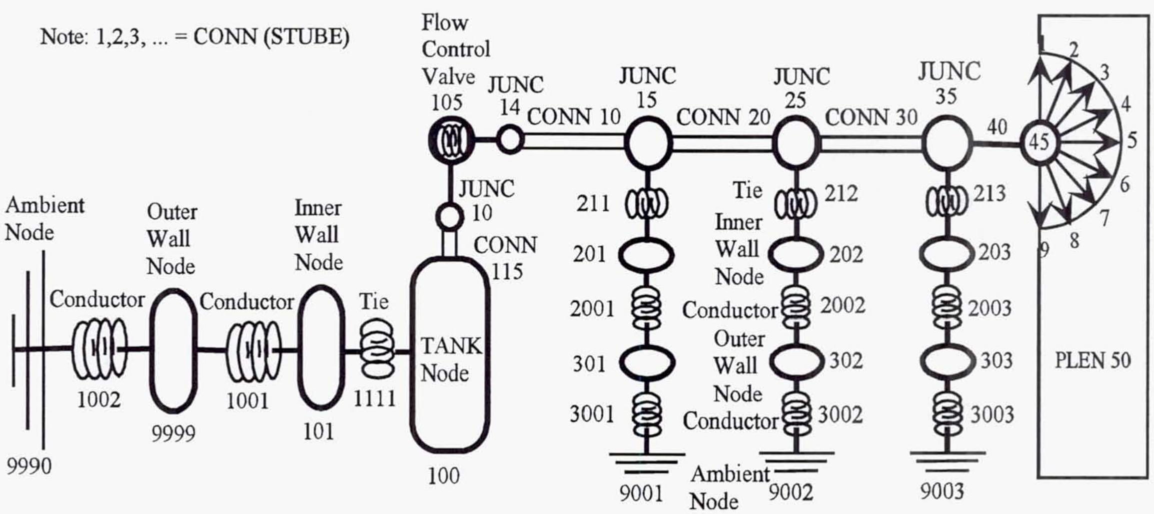

Figure 2 Schematic of The SINDA/FLUINT Model

The reliability of the modeling techniques used in this analysis was verified by Zhang[2] with the thermal analysis of shuttle GN_2 pressure control system. The following activities were conducted in Reference [2] to satisfy the requirements: (1) researched the shuttle flight data on a representative situation where a significant amount of GN_2 is used quickly (The shuttle GN_2 data of STS-71, STS-88, STS-95, and STS-96 missions were researched to find the high usage of the GN_2 during the shuttle cabin repress, or Mir space station repress, or International Space Station repress. Eventually the shuttle GN_2 data of STS-71 mission was chosen as the best data for the model simulating and comparison because the GN_2 usage of STS-71 mission is the highest among these four missions, and the GN_2 pressure has a significant drop during the shuttle cabin repress), (2) created a new model using the X-38 GN_2 tank modeling techniques as the basis, but with the different geometry and material properties of the Shuttle GN_2 tank, (3) used the new model to analyze the shuttle cases and compared the predicted results of the GN_2 pressure or temperature to the actual shuttle data. The results indicate that the model predictions of the pressure and temperature well match the actual shuttle data of STS-71 mission.

To simulate the heat transfer between the PFE tank wall and the gaseous CO_2, an additional heat transfer coefficient *(h_a)* was added to value calculated internally by FLUINT code. The empirical correlation[5] for the heat transfer coefficient *(h)* is listed as below:

$$h = \frac{k}{d}[(3.14 - 1.8t^b)\ln(\mathrm{Re}) - 2.55t^b + 4.25] \qquad (1)$$

Where

$$t = 1.0 - \frac{m}{M} \qquad (2)$$

$$b = 1.0 - \frac{50.6}{(\ln(\mathrm{Re}))^3} \qquad (3)$$

and

$$\mathrm{Re} = \frac{4G}{d\mu g_c} \qquad (4)$$

Where k is the thermal conductivity of the gaseous CO_2, d is the diameter of the PFE tank, Re is the Reynolds number for gaseous CO_2 flow, m is the current CO_2 mass, M is the initial CO_2 mass in the tank, G is the CO_2 mass flowrate, μ is the viscosity of the CO_2 gas, and g_c is the gravitational acceleration (sea level).

The empirical correlation (1) was aided greatly by performing the convergence tests and finding out that heat transfer coefficient h was independent of the tank thermal energy storage capacity (or capacitance) that is the product of the tank's density, volume and specific heat. Also the results of the convergence tests provided the general trend of the heat transfer coefficient h variation with time and with Reynolds number.

3.2 Requirements and Simulation Conditions

The PFE system is part of the integrated Temporary Sleep Station. It must be designed to meet minimum flow requirement. In addition, touch temperature requirement for the tank and the nozzle must also be met to preclude crew exposure to surface temperatures that can cause injury. The following items include initial conditions that were established and the requirements that have to be fulfilled for this analysis.

1. The model simulation starts at 0.0 and terminates at 50 seconds.
2. The initial pressure and temperature inside PFE tank is 860 psia and 72 °F. An ambient temperature of 72 °F is assumed.
3. The minimum flow requirement for the PFE system is to deliver 3.0 lbm CO_2 in 10 seconds and 5.5 lbm of CO_2 in 45 seconds during its operation.
4. The TeSS nozzle surface temperature should be kept above 40 °F.

4.0 PREDICTIONS OF PORTABLE FIRE EXTINGUISHER SYSTEM

The intent of this thermal analysis is to provide a better understanding of the thermodynamic performance of the PFE tank in the reduced gravity environment of space. The achievement of this goal requires the development of a SINDA/FLUINT model capable of simulating the laminar flow field and spatially varying thermodynamic properties within a discharging cylindrical vessel. The investigation of the mechanism of the heat transfer process within a cylindrical pressurized vessel has been completed. This effort is aided by the development of computer-plotted displays describing the pressure and temperature distributions throughout the discharge process.

The CO_2 flow calculation and the thermal analysis of the portable fire extinguisher system have been conducted using the SINDA/FLUINT model. The results are presented in the following order: (1) predictions of CO_2 flowrate and total discharged CO2 mass, (2) predictions of the thermal performance of PFE, and (3) Predictions of the Heat Transfer of PFE System.

4.1 Predictions of the CO_2 Flowrate and Total Discharged CO_2 Mass

Figure 3 shows the CO_2 discharge rate as a function of time. The discharge rate (flowrate) starts from 0.53 lbm/second at a start time of the simulation and quickly drops to 0.25 lbm/second in 10 seconds, and then it continually drops to 0.001 lbm/second in 25 seconds. This discharge rate gradually decreases to 0.0008 lbm/second at 45 seconds.

The total discharged CO_2 mass from the Portable Fire Extinguisher through the PFE TeSS nozzle is shown in Figure 4. The predicted initial CO_2 mass in the tank is 6.005 lbm that matches the qualification test data in reference [1]. The simulated result indicates that the total discharged CO_2 through the TeSS nozzle at 10 second and 45 second is 3.8 lbm and 5.5 lbm, respectively. After 50 seconds of operation, the total CO_2 mass remaining in the tank is approximately 0.35 lbm.

Figure 5 shows the CO_2 pressure in PFE tank. The compressed CO_2 gas is initially at a pressure of 860 psia and a temperature of 72 °F. This CO_2 pressure rapidly drops to 300 psi in 10 seconds due to high CO_2 discharge rate, and then it continually decreases to 89 psi in 22 seconds. After 22 seconds, this CO_2 pressure remains constant at 89 psi until end of simulation.

4.2 Predictions of the Thermal Performance of PFE

Figure 6 shows the temperatures of the CO_2 gas and PFE tank wall. The ambient temperature is also included in Figure 6 as a reference. As the result indicates, the CO_2 gas temperature in tank rapidly decreases from 72 ^oF to -69 ^oF in 22 seconds due to high CO_2 discharge rate and the extremely fast expansion of the CO_2 gas. The sensitive energy transfer from tank wall to CO_2 gas is very slow because the limited time. The PFE tank wall temperature drops to 70 ^oF in 22 seconds period of operation. This is because of the fast transient action between the tank wall and ambient, and the high thermal capacity of the tank structure. The tank wall temperature gradually decreases to 65.6 ^oF at the end of the simulation. From both the CO_2 pressure (Figure 5) and the CO_2 temperature (Figure 6), the simulation results suggest that the remaining CO_2 in the tank may be near the triple point (gas, liquid and solid) state.

Figures 7 and 8 show temperatures of the CO_2 gas, the nozzle cover wall, and the ambient. The simulation results for the first segment of the TeSS nozzle (at JUNC node 15) are shown in Figure 7. The CO_2 temperature drops from an initial value of 72 ^oF to -69 ^oF in 22 seconds, and the cover surface wall temperature only drops 5 ^oF in this period of time. After 22 seconds, the CO_2 temperature remains constant at -69 ^oF while the nozzle cover wall temperature continually drops and reaches at 43 ^oF at the end of the simulation. Figure 8 shows the simulation results for the second segment of the TeSS nozzle (at JUNC node 25). During the period of 21 to 23 seconds, the CO_2 temperature sharply rises from -69 ^oF to 2 ^oF because the PFE system is nearly running out of the flow. After 23 seconds, the CO_2 temperature gradually decreases from 2 ^oF to -13 ^oF at 50 seconds while the nozzle cover wall temperature continually drops and reaches at 50 ^oF at the end of the simulation.

Figure 9 shows the simulation results for the third segment of the TeSS nozzle (at JUNC node 35), where the cover (thermal insulation) is not applied. The situation of the CO_2 temperature profile for this segment is similar to the case of segment 2. From 21 to 23 seconds, the CO_2 temperature sharply rises from -69 ^oF to 27 ^oF because the PFE system is nearly running out of the flow. After 23 seconds, the CO_2 temperature gradually decreases from 27 ^oF to 20 ^oF at 50 seconds while the nozzle wall temperature continually drops and reaches at 36 ^oF at the end of the simulation. The results indicate that the nozzle wall temperature drop rate is gradually reduced because of the CO_2 temperature effect. The nozzle wall temperature at third segment of the TeSS nozzle is lower than the nozzle cover wall temperatures for the first two segments; this is because that there is no insulation cover on this segment.

4.3 Predictions of the Heat Transfer of PFE System

The heat transfer rates were predicted for both of PFE CO_2 tank and TeSS nozzle. Figure 10 shows the heat transfer rates of PFE system. For the PFE tank, the heat transfer rate from 0 rapidly increased to 360 But/hr in 22 seconds. This is because that the CO_2 mass was discharged at a much higher rate and the CO_2 gas temperature was dropped rapidly due to the gas expansion. After 22 seconds, the heat transfer rate for PFE tank is almost kept at a constant until the end of the simulation. This is because the CO_2 gas temperature in the tank is kept at a constant value (-69 ^oF), and the PFE tank wall temperature is gradually dropped from 70 ^oF to 65.6 ^oF after 22 seconds. The heat transfer rates for three segments of the

TeSS nozzle have same value in 22 seconds. The highest rates for these three segments are the 120 Btu/hr, which is one-third of the heat transfer rate of the PFE tank. This is because the heat transfer area of the TeSS nozzle is much smaller than the heat transfer area of the PFE tank. After 22 seconds, the heat transfer rates for these three segments are different. The first segment of the TeSS nozzle has the highest value, which is gradually reduced from 120 Btu/hr (highest point) to 80 Btu/hr at the end of the simulation. The heat transfer rates for other two segments are the constant after 22 seconds.

Figure 11 shows the heat transfer coefficient (Nusselt Number versus Reynolds number) for PFE tank system. The result indicates that the flow status in the tank is the laminar flow or transient flow during the entire operation period. The detailed results of heat transfer calculation for the PFE tank are shown in the table as below.

Selected Results of Heat Transfer Calculations for PFE Tank

t [Sec.]	P_{tank} [psia]	G [lb/hr]	m [lbm]	T_{CO2} [^{O}F]	T_{tank} [^{O}F]	M_{total} [lbm]	μ [lbm/ft-hr]	Re	Nu_d
0.00	860.0	0.0	5.90	72.0	72.0	0.00	0.0358	0	1.7
1.05	776.1	1804.8	5.36	61.4	72.0	0.54	0.0351	78577	37.0
2.06	711.1	1712.2	4.87	54.7	72.0	1.03	0.0346	75605	35.0
3.00	652.9	1625.5	4.44	48.3	71.9	1.46	0.0342	72602	33.2
4.05	590.1	1526.5	3.98	40.9	71.9	1.92	0.0338	68986	31.3
5.10	529.8	1426.4	3.55	33.3	71.8	2.35	0.0333	65433	29.6
6.07	476.7	1330.0	3.18	25.9	71.8	2.72	0.0328	61958	28.1
7.12	422.9	1227.5	2.81	17.9	71.7	3.09	0.0323	58045	26.5
8.48	358.7	1092.7	2.37	7.1	71.6	3.53	0.0316	52803	24.5
9.99	295.7	946.1	2.05	-5.0	71.4	3.85	0.0307	47084	23.0
11.85	232.0	737.2	1.63	-19.5	71.2	4.28	0.0298	37789	20.7
13.65	183.6	579.1	1.20	-32.7	71.0	4.70	0.0289	30613	19.6
15.90	138.0	426.2	0.90	-48.1	70.7	5.01	0.0278	23415	18.1
22.00	89.9	5.9	0.56	-69.8	69.7	5.34	0.0262	350	10.5
25.20	89.8	3.0	0.53	-69.8	69.2	5.37	0.0262	175	9.6
29.10	89.8	2.9	0.48	-69.8	68.6	5.42	0.0262	172	9.0
34.20	89.8	2.9	0.46	-69.8	67.9	5.44	0.0262	172	8.9
38.70	89.8	2.9	0.44	-69.8	67.2	5.46	0.0262	170	8.8
45.00	89.8	2.8	0.40	-69.8	66.3	5.50	0.0262	170	8.6
49.68	89.8	2.8	0.36	-69.8	65.6	5.54	0.0262	170	8.4

Where t is the model simulation time, P_{tank} is the CO_2 pressure of PFE tank, G is the CO_2 mass flowrate, m is the CO_2 mass remaining in the tank, T_{CO2} is the CO_2 gas temperature in the tank, T_{tank} is the tank wall temperature, M_{total} is the total discharged CO_2 mass at a current time, μ is the viscosity of the CO_2 gas, Re is the Reynolds number, and Nu_d is the Nusselt number ($Nu_d = (hd)/k$).

5.0 CONCLUDING REMARKS

The thermal analysis of the portable fire extinguisher system including PFE tank and TeSS nozzle has been performed with a SINDA/FLUINT model. The simulation results are provided which define the variation of the gas discharge temperature and minimum gas temperature throughout the discharge process for a real gas in the space environment. An investigation of the mechanism of the heat transfer process within a cylindrical vessel is evaluated. This effort is aided by the development of describing the distributions of the velocity, pressure, and temperature of the CO_2 throughout the discharge process. Total simulation time is 50 seconds. The simulation results can be summarized as follows:

1. The flow simulation results show that the CO_2 discharge rates fulfill the design requirement. The total CO_2 discharged from the PFE tank through the TeSS nozzle at 10 second and 45 second is 3.8 lbm and 5.5 lbm respectively. The minimum flow requirement is 3.0 lbm of CO_2 in 10 seconds, and 5.5 lbm of CO_2 in 45 seconds per PFE vendor (ARDE Inc.). The TeSS nozzle design passes the minimum requirement.

2. The thermal analysis results show that the CO_2 temperature in tank decreases from 72 ^oF to -69 ^oF while the CO_2 pressure in tank drops from 860 psia to 89 psia in the first 22 seconds. After 45 seconds, the CO_2 tank wall temperature is 65.6 ^oF, and the TeSS nozzle cover wall temperatures for the three segments are 47 ^oF, 53 ^oF and 37 ^oF, respectively. The nozzle temperature in third segment (CONN 30) is lower than that of other two segments (CONN 10 and CONN 20) due to the effect of the thermal insulation cover.

3. The predicted results show that the heat transfer rates increase with increasing the discharge CO_2 masses for both of the PFE tank and TeSS nozzle in 22 seconds. After 22 seconds, the heat transfer rate of the PFE tank is almost kept at a constant value until the end of the simulation. The heat transfer rates for three segments of the TeSS nozzle are decrease with increasing the length of the TeSS nozzle. Starting from 23rd seconds, the heat transfer rate for the first segment of the TeSS nozzle is gradually reduced from 120 Btu/hr (highest point) to 80 Btu/hr at the end of the simulation because of the temperature difference decreasing.

6.0 REFERENCES

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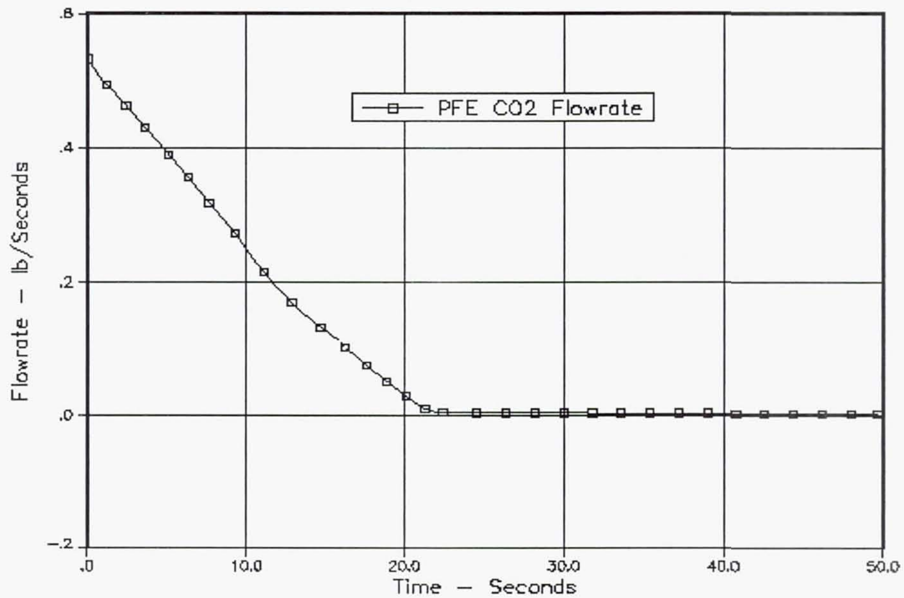

Figure 3 CO_2 Flowrate of the portable fire extinguisher system

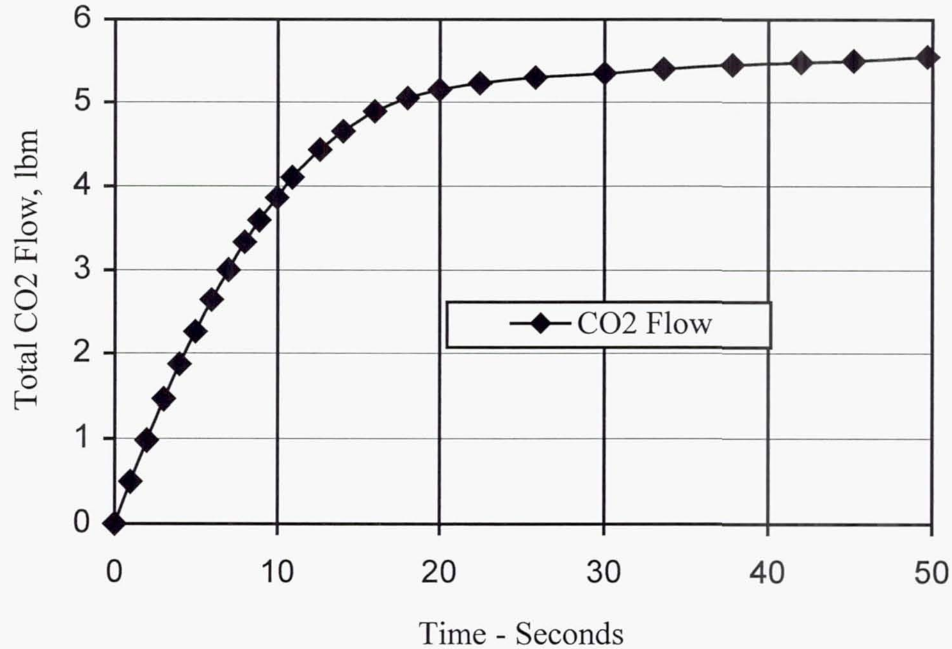

Figure 4 Total Discharged CO_2 Flow During the PFE Operations

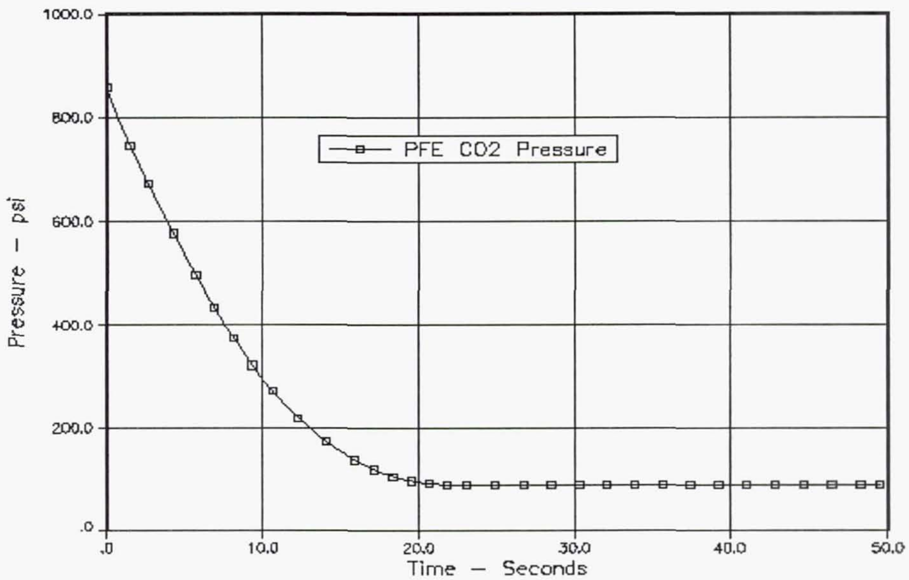

Figure 5 CO_2 pressure of the portable fire extinguisher system

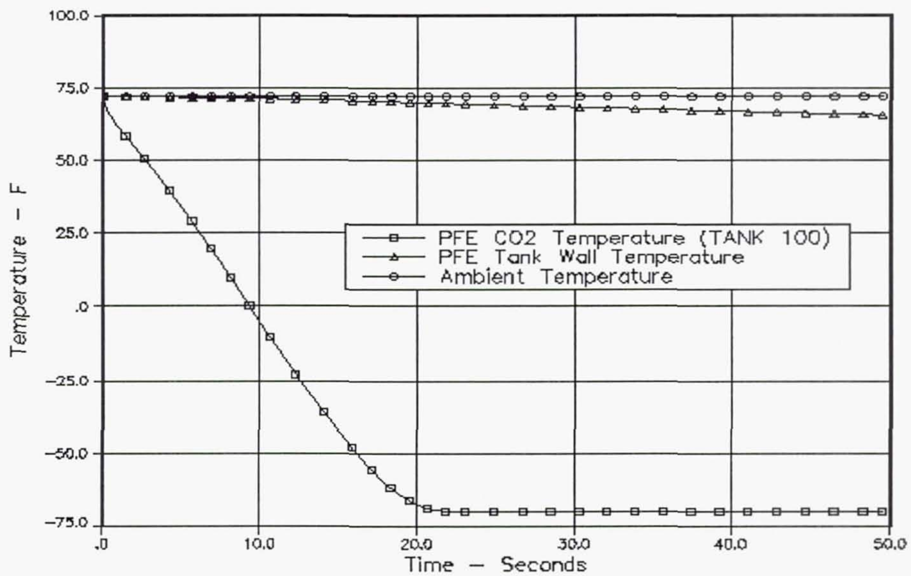

Figure 6 Temperatures of the CO_2, tank wall and ambient of the tank

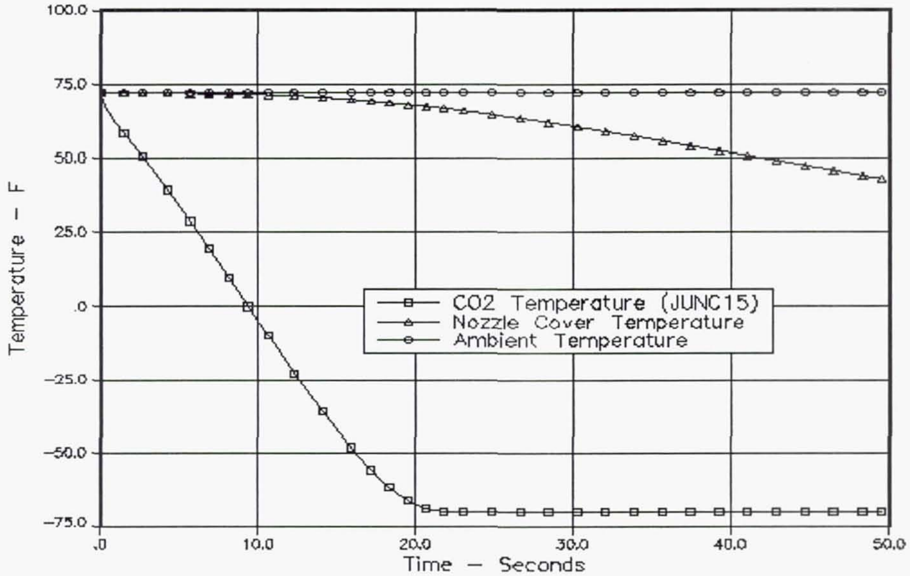

Figure 7 Temperatures of the CO_2, cover and ambient of the nozzle at JUNC 15

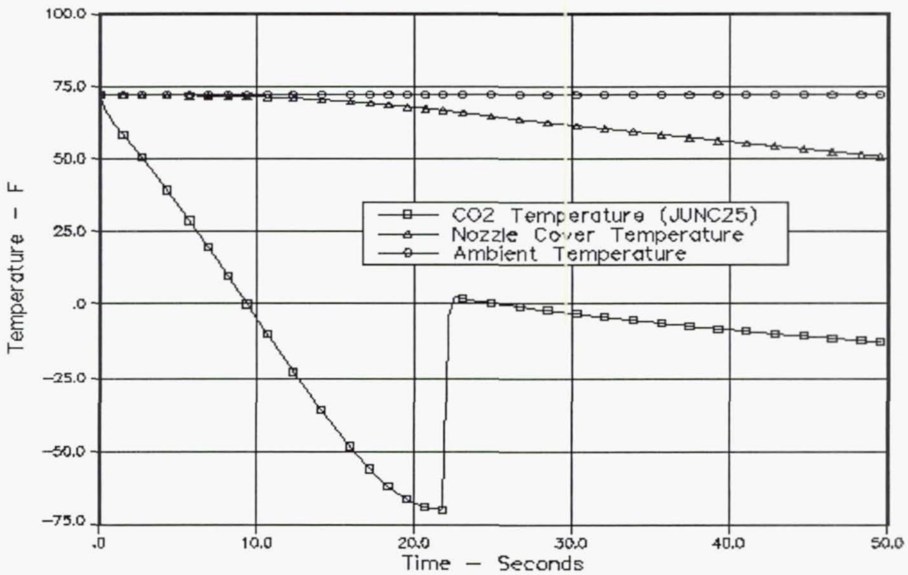

Figure 8 Temperatures of the CO_2, cover and ambient of the nozzle at JUNC 25

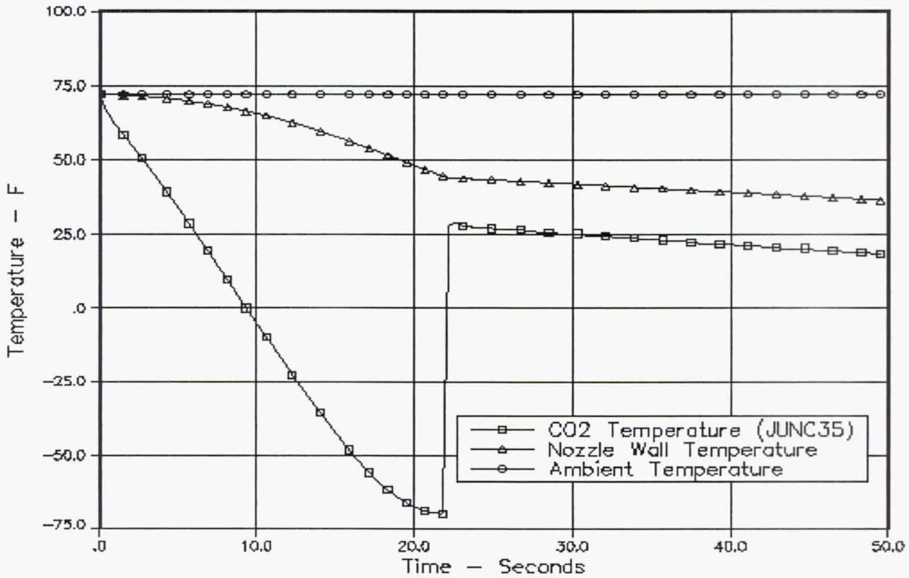

Figure 9 Temperatures of the CO_2, wall and ambient of the nozzle at JUNC 35

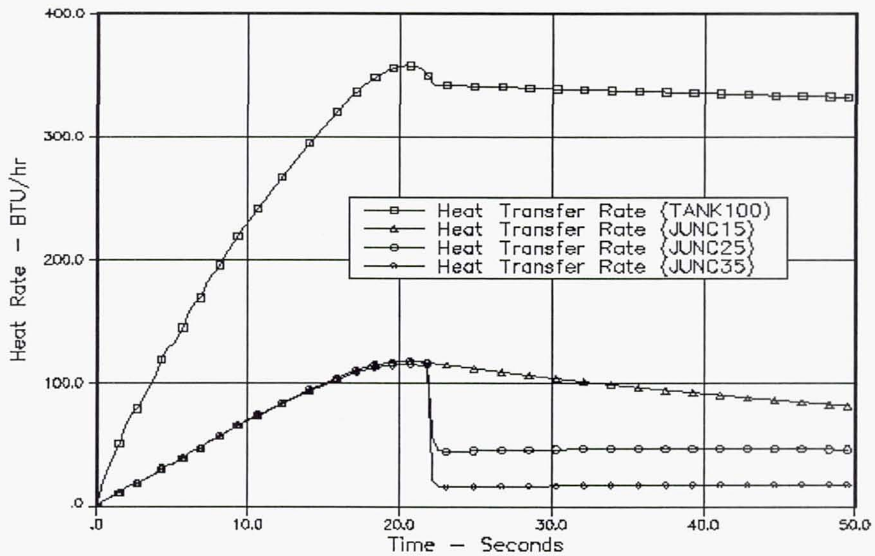

Figure 10 Heat Transfer Rate of PFE System

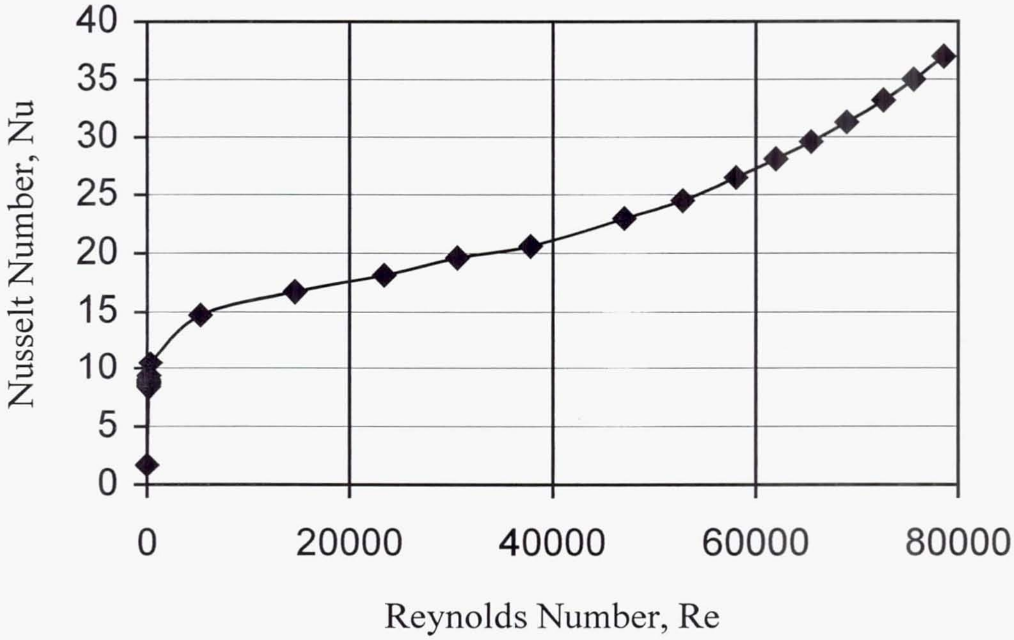

Figure 11 Heat Transfer Between PFE Tank Wall and Gaseous CO_2