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Prediction of dry ice mass for firefighting robot actuation

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Abstract. The limitation in the performance of electric actuated firefighting robots in high-temperature fire environment has led to research on the alternative propulsion system for the mobility of firefighting robots in such environment. Capitalizing on the limitations of these electric actuators we suggested a gas-actuated propulsion system in our earlier study. The propulsion system is made up of a pneumatic motor as the actuator (for the robot) and carbon dioxide gas (self-generated from dry ice) as the power source. To satisfy the consumption requirement (9cfm) of the motor for efficient actuation of the robot in the fire environment, the volume of carbon dioxide gas, as well as the corresponding mass of the dry ice that will produce the required volume for powering and actuation of the robot, must be determined. This article, therefore, presents the computational analysis to predict the volumetric requirement and the dry ice mass sufficient to power a carbon dioxide gas propelled autonomous firefighting robot in a high-temperature environment. The governing equation of the sublimation of dry ice to carbon dioxide is established. An operating time of 2105.53s and operating pressure ranges from 137.9kPa to 482.65kPa were achieved following the consumption rate of the motor. Thus, 8.85m^3 is computed as the volume requirement of the CAFFR while the corresponding dry ice mass for the CAFFR actuation ranges from 21.67kg to 75.83kg depending on the operating pressure.

1. Introduction

Power systems for firefighting robot (FFR) applications are dominated by engines or electric motors (dc motor). The electric actuators are efficient in performance in ordinary temperature environment but are unreliable in a high-temperature environment [1-2] which characterizes an indoor fire emergency. This is because electric actuators are not designed to function in severe temperature in addition to the loss of their magnetic and piezoelectric properties at such temperatures [2].

Research trends on firefighting robot that can operate in a high-temperature environment (fire emergency) are limited in literature because the majority of the existing literature is inclined towards the preventive task of firefighting. Thus, development of fire detection systems and algorithm take the central stage of studies in firefighting robot applications [3] and little attention is paid to mobility in the high-temperature environment.

Up till now, water-hydraulic-powered and gas-powered actuators have emerged as alternatives to electric-powered actuators in FFR applications. The water-powered actuator is the heart of a water-hydraulic propulsion system (WHPS) proposed in the studies of Zhang et al. [1] and Liljeback, Stavdahl, & Beitnes [4]. The WHPS is composed of a hydraulic motor (as the actuator) and water as the powering fluid instead of oil. As Zhang et al. [1] adopted the WHPS for an indoor firefighting robot which is remotely controlled, Liljeback, Stavdahl, & Beitnes [4] implemented the WHPS on a snake firefighting robot in a tunnel fire (outdoor) application. The FFR developed in both studies lack self-power ability required for efficient operation of an FFR in a fire emergency.

Gas-powered actuators have been applied majorly in the area of material handling of equipment. Examples include linear actuators that are developed to function under high temperatures [2],[5],[6]. The application of gas-powered actuators in firefighting robot led to the concept of the gas-actuated propulsion system (GAPS). Thus, GAPS is composed of a pneumatic actuator (linear or rotary) and a compressed air or gas as its power source. While Ono & Kato [7] introduced a rubber bellow based pneumatic actuator as a GAPS for the mobility of a pipe inspection robot (an outdoor application), Ajala, Khan, Shafie, & Salami [8] proposed a carbon-dioxide gas powered autonomous firefighting robot (CAFFR) for firefighting inside a high temperature fire environment.

Implementing the GAPS for firefighting application as suggested in our previous study [8] requires that the gas is self-generated within the FFR and produced in quantity enough to sustain the operation of FFR inside the fire. Consequently, it becomes critical to determine the volume of carbon dioxide gas as well as the mass of dry ice that will provide sufficient power to drive and actuate the gas driven motor. This is because the CAFFR, adopting GAPS concept, is projected to self-generate the carbon dioxide gas from dry ice within the robot. The schematic of achieving the power for the CAFFR actuation is shown in figure 1.

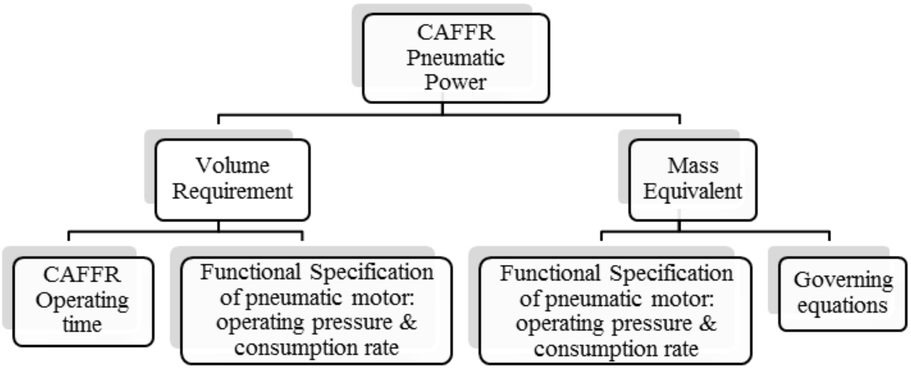

Figure 1. Schematic diagram of power required for CAFFR actuation

Figure 1 shows the schematic of producing the required power for CAFFR actuation. From the figure, the volume of carbon dioxide gas and corresponding mass of dry ice required for the CAFFR performance rest on functional specifications such as the consumption rate of the pneumatic (air) motor and the operating pressure of the motor. Also, the volume requirement can be achieved once the operating period of the CAFFR is known. Additionally, the corresponding mass of dry ice can be determined when the governing equations are established. As a result, this paper focuses on determining analytically the volume of carbon-dioxide gas as well as the mass of dry ice required to sustain the actuation of a CAFFR. The rest of this report is organized as follows: Section 2 specifies the operating time and the volume requirement of the robot. Analysis and modeling equation for predicting the mass of dry ice required to operate the CAFFR are presented in section 3 while the summary and conclusion are given in section 4.

2. Required Volume of CO_2 gas for the CAFFR Operation time

2.1. Specification for the CAFFR Operating time

In this paper, the burning time for the projected fire scenario will be used to describe the operating time of the CAFFR. So, this research adopted the fire scenario model used in the study of Lai, Tsai, & Chen [9]. A modified furnished office room dimension was used. Consequently, the office room dimension was specified as 6m length x 5m wide x 2.4m high, with a 0.6m wide x 1.8m high door. A fire load (E_f) of 11892MJ amounting to an approximate fire load density e_f of 390MJ/m^2 [9] is specified. Equation (1), adopted from Buchanan [10], was used to determine the burning time of the fire scenario. This time was thereafter employed as the robot operating time in the fire. A burning time of 2105.53s (approximately 35mins) resulted from the calculation. Thus, the operating period of the CAFFR shall be for thirty-five minutes (35mins).

$$t_b = \frac{E_f}{\Delta H_c}\left[0.18A_v\left(\frac{H_v W}{D}\right)^{1/2}\left(1 - e^{-0.036\Omega}\right)\right]^{-1} \quad (1)$$

where, t_b = burning time (s), E_f = Fire (fuel) load (MJ), ΔH_c = Heat of combustion, A_v = Area of door opening (m^2), H_v =Door Height (m), W = Room width (m), D = Depth of room (m), and Ω = Opening factor. The details of A_v and Ω are given in the appendix

2.2. Required Volume to actuate the CAFFR

We have proposed an FFR that can successfully operate in a high-temperature fire environment which will have the capability to return for fueling/ refueling. The selected air motor (Model No LG30FT) requires a gas supply (consumption rate) of 0.004248m^3/s [11]. Based on this consumption rate, the volume of the carbon dioxide gas that can drive the air motor for selected operating periods is computed and the result is tabulated in Table 1.

Table 1. Computed Volume requirement of $CO_{2\,(g)}$ to power a pneumatic motor.

Operating Time (s)	600	1200	1800	2400	3000	3600
Volume (m^3)	2.55	5.10	7.65	10.20	12.74	15.29

The required volume was plotted as a function of the operating time of the CAFFR and the resulting graph is shown in figure 2. A linear model presented in equation (2) was selected to establish the relationship between the volume of the carbon dioxide gas required to actuate the CAFFR and the operating time of CAFFR in the fire spot. The model has a slope (coefficient of t_b = 0.0042) which represents the consumption rate of the pneumatic motor, a coefficient of determination (R^2) value of 1, and a standard deviation of 0.00324. With a *p-value* of <0.0001, the operating time had a significant linear effect on the volume of carbon dioxide required to power CAFFR. The model was subsequently used to predict the volume of carbon dioxide gas at the calculated operating time of 2105.53s. Thus, a volume of 8.85m^3 of carbon-dioxide gas will be required for the mobility of the CAFFR inside the fire spot.

$$V_{CO_{2(g)}} = 0.0042t_b + 0.0047 \quad (2)$$

where, $V_{CO_{2(g)}}$ is volume of $CO_{2\,(g)}$ (m^3), and t_b is now referred to as the operation time (s).

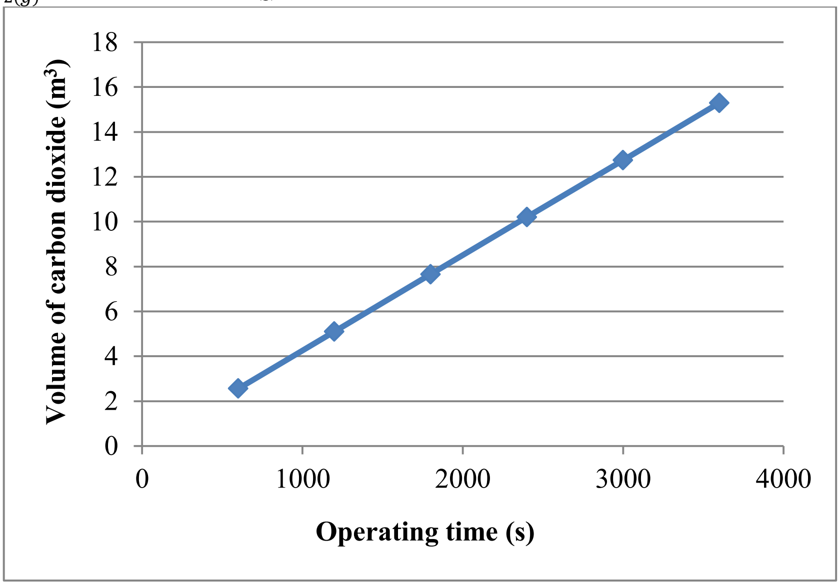

Figure 2. The plot of the volume of carbon dioxide required to power CAFFR

3. Equivalent Mass of Dry Ice

3.1. Governing Equation

A literature search on the solid-gas relationship of dry ice revealed that existing data from literature and dry ice manufacturers lack details as displayed in Table 2. The available data either covers a limited area or parameter (like the temperature of operation) is missing which makes the information inadequate. Thus, the computation of the equivalent mass of dry ice that will produce a given volume of carbon dioxide gas is examined and benchmarked with the existing data.

Table 2. Existing information.

S/N	Mass of Dry Ice (kg)	Volume of $CO_{2(g)}$ (m^3)	Temperature ($^{\circ}C$)	Source of Information
1	0.430	0.2180	25	Wu, Kitagawa, & Tsukagoshi [12]
2	0.454	0.2500	Not Specified	DryIceProduction [13]
3	0.454	0.2500	Not Specified	Caldwell, Lewis, Shaffstall, & Johnson [14]; Airgas [15]
4	1	0.5457	21.1	AIRPRODUCT [16];

Computational analysis of different hypothetical dry ice masses at temperatures commonly used in the literatures (15.6°C, 20°C, 21.1°C, 25°C and 27°C) was performed. It was discovered that the ideal gas equation displayed in equation (3) can approximate the relationship between dry ice mass and the volume of carbon dioxide gas produced. The result of the computation was presented in Table 3.

$$PV = nRT \tag{3}$$

where, P = Pressure (kPa), n = No of moles (mol), R = Universal gas constant, T = Temperature (K)

Table 3. The volume of Carbon dioxide gas produced from a given mass of dry ice.

Mass (kg)	Volume[1] at selected temperatures				
	15.6°C	**20°C**	**21.1°C**	**25°C**	**27°C**
0.005	0.0027	0.0027	0.0027	0.0028	0.0028
0.01	0.0054	0.0055	0.0055	0.0056	0.0056
0.015	0.0081	0.0082	0.0082	0.0083	0.0084
0.02	0.0108	0.0109	0.0110	0.0111	0.0112
0.044	0.0237	0.0241	0.0242	0.0245	0.0246
0.1	0.0539	0.0547	0.0549	0.0556	0.0560
0.43	0.2316	0.2352	0.2360	0.2392	0.2408
0.45	0.2424	0.2461	0.2470	0.2503	0.252
0.454	0.2446	0.2483	0.2492	0.2525	0.2542
0.5	0.2693	0.2734	0.2745	0.2781	0.2800
1	0.5387	0.5469	0.5489	0.5562	0.5599

[1]Volumes are computed using equation (4) for P = 101.325 kPa, R = 8.3145 $Pa m^3 K^{-1} mol^{-1}$

Observations of the data in Table 3 show that 0.43kg (430g) mass of dry ice will sublime to give 0.2392 m^3 of CO_2 gas (green color legend). This gives a value of 0.0212 higher than the experimental volume recorded in the study of Wu, Kitagawa, & Tsukagoshi (2005). The sublimation temperature which was not specified in Caldwell, Lewis, Shaffstall, & Johnson, (2006) and Airgas (2002) was discovered to be 20°C (blue color legend). Also, the computed volume of the gas is recorded as 0.2482 m^3 with a 0.0018 difference to the existing value. A 1kg mass of dry ice is computed to produce 0.5466m^3 of carbon dioxide gas at 21.1°C (yellow color legend).

Table 4 shows the comparison between the existing and the predicted volume of carbon dioxide. The predicted values are very close to the existing values and root mean squared error of 0.00123 was recorded.

Table 4. Comparison of existing and computed volume of CO_2 gas from a given mass of dry ice.

S/N	Mass of Dry Ice (kg)	Temperature (°C)		Volume (m^3)		RMSE
		Existing	Predicted	Existing	Predicted	
1	0.430	25	25	0.218	0.2392	0.0123
2	0.454	Not Specified	20	0.250	0.2482	
3	1	21.1	21.1	0.5457	0.5466	

Predicting the actual mass of dry ice that will power the air motor for the operation time of the CAFFR requires further analysis of Table 3 in terms of the varying operating pressure of the pneumatic motor. This is because there are speed and torque variation in the real operation of CAFFR. Thus, the mass of dry ice required to produce the 8.85m^3 volume of carbon dioxide is dependent the operating pressure. Hence, a computation of the mass of dry ice at different operating pressures of the air motor is required.

3.2. Specification for CAFFR Operating Pressures

Pneumatic motors are powered with pressures ranging from 137.9kPa to 1034.25kPa though 620.55kPa remains the optimum operating pressure of a pneumatic motor. Also, carbon dioxide gas phase diagram (figure 3) revealed that the critical pressure of the gas is 517.13kPa (triple point pressure). At this pressure, the gas exists in its three phases. But the liquid is not desirable for this work, so our design pressure should be less than 517.13kPa which will make the interaction remains as solid-gas expansion. As a result, the operating pressures of the CAFFR range from 137.9kPa to 482.65kPa. This pressure range is therefore used to determine the mass equivalent. Hence, the equivalent mass is computed by using equation (4). Equation (4) was realized by expressing equation (3) in terms of the operating pressure and a given mass of dry ice. The result is displayed in Table 5.

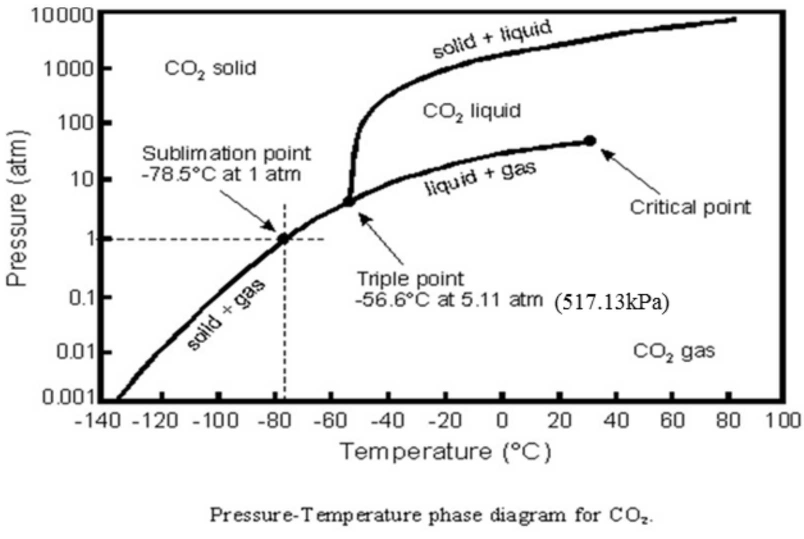

Figure 3. Phase diagram of carbon dioxide (Photo reprinted from Stevengoddard) [17].

$$\frac{p}{m_d} = k \tag{4}$$

where, m_d (kg) is a given mass of dry ice, and P is operating pressure (kPa)

Table 5. Computation of the mass equivalent of the required volume of dry ice for different operating pressures @ 25°C

Pressure (kPa)	**Mass of dry Ice (kg)**
137.90	21.67
206.85	32.50
275.80	43.33
344.75	54.17
413.70	65.00
482.65	75.83

The result of the plot of dry ice mass as a function of the operating pressure is displayed in figure 4. A linear model represented by equation (5) was selected to establish the relation between the mass of dry ice (m_d) required to actuate the CAFFR and the operating pressure of the pneumatic actuator (P_{motor}). The operating pressure linear effect on the dry ice mass was quite significant with a *p-value* of <0.0001. The linear model had an R^2 value of 1, and a standard deviation of 0.00293. The inverse of the slope of the graph (coefficient of P_{motor} = 0.1571) represents the actual value of k in equation (4). It was discovered that for every 68.95kPa (10psi) rise in pressure an approximate 10.83kg (68.95×0.1571) mass of dry ice is consumed.

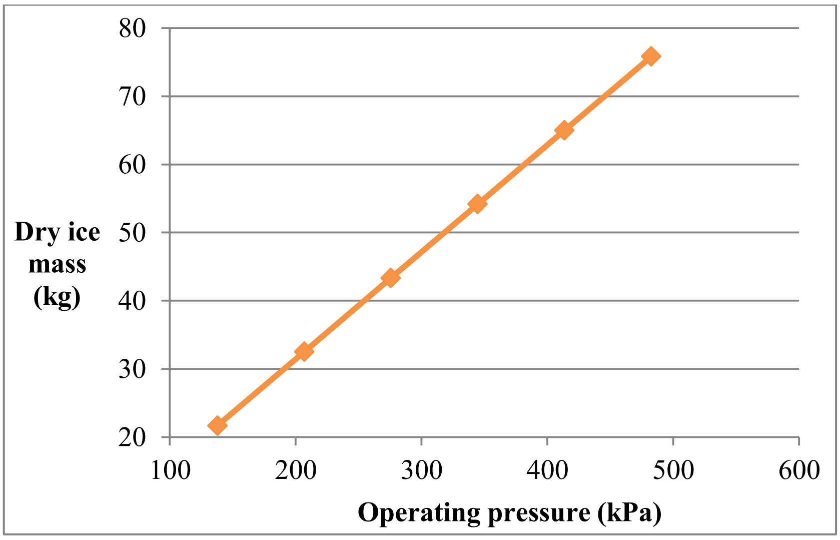

Figure 4. The plot of dry ice mass required to power an FFR for different operating pressures.

$$m_d = 0.1571 P_{motor} - 1 * 10^{-13} \tag{5}$$

Validation of the model equation was achieved by comparing the computation using equation (4) and predictions using the linear model in equation (5). The result is displayed in Table 6. An RSME value of 0.00816 was obtained. Thus, the dry ice mass required to power CAFFR at the selected operating pressures range from 21.67kg to 75.83kg.

Table 6. Comparison of computed and predicted mass of dry ice required to power CAFFR.

Pressure (kPa)	Mass (kg) using equation (4)	Mass Prediction from the model equation	RMSE
137.9	21.67	21.66	
206.85	32.50	32.50	
275.8	43.33	43.33	0.00816
344.75	54.17	54.16	
413.7	65.00	64.99	
482.65	75.83	75.82	

4. Conclusion

The amount of carbon-dioxide gas that would make a firefighting robot, CAFFR, designed to operate successfully in an indoor fire emergency is discussed. It was established that the ideal gas equation can be used to determine the volume of carbon-dioxide gas that can be produced from a given mass of dry at any temperature. Different masses of dry ice were examined using this equation and the corresponding volumes of carbon dioxide gas were calculated. The computed volumes were validated using the existing information on mass to volume sublimation of dry ice. Base on the consumption rate of the motor, operating pressures ranging from 137.9kPa to 482.65kPa was specified for the power of the CAFFR. Furthermore, a mathematical model was developed for the actual mass of dry ice that can conveniently power the CAFFR for the operation time of 2105.53s and the different operating pressures. It was discovered that the mass equivalent depends upon the operating pressure. Thus the actual dry ice mass ranges from 21.67kg to 75.83kg depending on the operating pressure used.

Appendix

$$A_v = H_v \times W_d; \tag{2.1}$$

$$\Omega = \frac{A_t - A_v}{A_v (H_v)^{1/2}} \tag{2.2}$$

$$A_t = 2(l_1 l_2 + l_1 l_3 + l_2 l_3); \tag{2.3}$$

A_t= Total internal surface area of the office room (m^2), l_1 = Length of room (m), l_2 = Width of room (m), and l_3 = Height of room (m), W_d = Width of door (m)

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