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MECHANICAL ENGINEERING | RESEARCH ARTICLE

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Optimization of CO₂ production rate for firefighting robot applications using response surface methodology

M. T. Ajala¹,²*, Md R. Khan³, A. A. Shafie¹, M. J. E. Salami³, M. I. Mohamad Nor⁴ and M. O. Oladokun⁵

Abstract: A carbon dioxide gas-powered pneumatic actuation has been proposed as a suitable power source for an autonomous firefighting robot (CAFFR), which is designed to operate in an indoor fire environment in our earlier study. Considering the consumption rate of the pneumatic motor, the gas-powered actuation that is based on the theory of phase change material requires optimal determination of not only the sublimation rate of carbon dioxide but also the sizing of dry ice granules. Previous studies that have used the same theory are limited to generating a high volume of carbon dioxide without reference to neither the production rate of the gas nor the size of the granules of the dry ice. However, such consideration remains a design requirement for efficient driving of a carbon dioxide-powered firefighting robot. This paper investigates the effects of influencing design parameters on the sublimation rate of dry ice for powering a pneumatic motor. The optimal settings of these parameters that maximize the sublimation rate at the minimal time and dry ice mass are presented. In the experimental design and analysis, we employed full-factorial design and response surface methodology to fit an acceptable model for the relationship between the design factors and the response variables. Predictive models of the sublimation rate were examined via

Public Interest Statement: Electric motor powered robots cannot operate close to fire spots because of the risk of insulation breakdown of the engines. A carbon dioxide (CO₂) gas-powered pneumatic actuator that can self-generate CO₂ in situ from dry ice has been proposed to replace the electrical motors and make actuator operable in indoor firefighting application.

To generate the CO₂ effectively from dry ice for the pneumatic power task, the effects of the influencing factors such as the mass of dry ice and the temperature of water—used as to speed up the production rate of carbon dioxide—on the sublimation rate of carbon dioxide from dry ice is examined in the current article.

Although the pneumatic motor, in this study, will be used to propel a firefighting robot in the high thermal indoor fire; the same approach is applicable for converting solid CO₂ into gas form for other applications.
ANOVA, and the suitability of the linear model is confirmed. Further, an optimal sublimation rate value of 0.1025 g/s is obtained at a temperature of 80°C, the mass of 16.1683 g, and sublimation time of 159.375 s.

Subjects: Power & Energy; Robotics & Cybernetics; Mechatronics

Keywords: air motor; dry ice; firefighting robot; Gas actuator; indoor fire; Phase Change Materials (PCM); pneumatic actuator; pneumatic motor; response surface methodology; sublimation rates

1. Introduction

Fire disasters around the world have continuously caused significant human casualties and collateral losses, and often, well-trained firefighters may succumb to injuries. The 68,085 firefighters’ injuries that occurred in the line of duty during the year 2016 (Haynes & Molis, 2016) suggest that firefighting still presents great risks of personal injury to firefighters. Leveraging on the recent technological developments, robots are being used to lessen the injuries of firefighters and increase their work performance. As such, firefighting robot (FFR) are being developed for both indoor and outdoor applications with a broad objective of replacing and assisting the firefighters (Amano, 2002).

Research trends in the developments of FFR have shown that little attention has been paid to the design of the propulsion systems (AlHaza, Alsadoon, Alhusinan, Jarwali, & Alsaiif, 2015), especially in extreme temperature. The mode of propulsion of the majority of the FFRs is by electrical power which has an unreliable performance in the extreme temperatures (Zhang, Kitagawa, & Tsukagoshi, 1999). Therefore, mobility and survival of FFR under high-temperature environment become a significant research area. As such Zhang et al. (1999) proposed a water-powered hydraulic propulsion system (WHPS) for the mobility of FFR in a severe temperature environment. The WHPS composed of a hydraulic motor as the actuator and water as the powering fluid instead of oil. The same mechanism was employed for a snake firefighting robot in a tunnel fire application by Liljeback, Stavdahl, and Beitnes (2006). However, while the latter has been designed for an outdoor application, the former lacks autonomous characteristic as required for current FFR.

To overcome the above challenges, a gas-actuated FFR is proposed in our earlier study (Ajala, Khan, Shafie, & Salami, 2016). The study conceived a novel carbon dioxide (CO₂) gas-powered autonomous firefighting robot (CAFFR). The said CAFFR is designed to be propelled by a pneumatic motor that is powered by in situ generated CO₂ gas from dry ice. Findings from the preliminary investigations revealed the possibility of generating low-pressure CO₂ gas as a power source for the gas-driven motor.

The CAFFR adopted the concept of phase change of materials (PCM) as its underlining theory. The theory was used to develop actuators (mainly linear actuators) that operate under the high thermal environment (Suzumori, Matsuoka, & Wakimoto, 2012; Matsuoka, & Suzumori, 2014; Matsuoka, Suzumori, & Kanda, 2016). These developments have been applied majorly in the area of material handling of equipment. Also, PCM was introduced in a robotic application with the development of a rubber bellow-based pneumatic actuator for the mobility of a pipe inspection robot (Ono & Kato, 2010).

Similarly, PCM has been used to develop pressure sources that drive pneumatic actuators. A reversible reaction of water electrolysis was employed to generate gas pressure for pneumatic actuators (Suzumori, Wada, & Wakimoto, 2013), which was used as a power source for an untethered robot (Kitamori, Wada, Nabe, & Suzumori, 2016). Kitagawa et al. (2005) also proposed a portable pneumatic power source using the sublimation of dry ice to CO₂ gas. The devices above are limited in performance to the normal environment as against severe temperature environment. The mobility of the FFR in a high thermal environment, therefore, remains a concern.
The dry ice solid–gas phase transition has various application areas. Its sublimation to produce a large volume of CO$_2$ gas has been used to wipe out bed bugs in Nanoudon & Chonbang (2014). The effect of cloudy and non-cloudy air on the sublimation rate (SR) of dry ice was investigated by Kochtubajda & Lozowski (Kochtubajda & Lozowski, 1985). The study concluded that sublimation is faster in a warm, cloudy air and the result was used for cloud seeding. The sublimation of dry ice into gas in clear air was investigated in the experimental study of Winkel (2012). The production rate of CO$_2$ from dry ice was modeled, and the resulting model revealed that the SR of dry ice was proportional to its surface area. However, the majority of these applications have focused on producing a high volume of CO$_2$, while production time is not treated as a factor because of the application areas. For propulsion application where CO$_2$ will be used as a power source, both the volume and the sublimation time (ST) remain a design criterion.

To deliver sufficient power to drive the gas-driven motor, determination of the volume of CO$_2$ gas and mass of dry ice is critical. The following benchmark parameters, namely burning time for the fire scenario and volume of CO$_2$ gas are required to power the motor was computed in an earlier study (Ajala, Khan, Shafie, & Salami, 2017). From the study, we observed that the gas volume needed for a given time is a function of the mass of the dry ice and its SR. However, as dry ice SR is proportional to its surface area (Winkel, 2012), it becomes critical to determine the minimal size of dry ice that provides optimal SR at the shortest possible time. For instance, subliming the mass (say 30 g, for example) as a singular unit takes longer time than separate granules (say three 10 g sizes or two 15 g sizes). Hence, although the SR is critical to power the gas motor, the dry ice size also remains a design constraint. Also, increasing the rate of sublimation of dry ice is desirable at a relatively short burning time. According to Winkel (2012), dry ice sublimes faster in a warm environment than in cold ones. As a result, hot water is proposed as a means of speeding up the dry ice SR. Hence, with these underlying constraints, we selected dry ice mass and water temperature to optimally assess the sublimation of dry ice in a warm environment.

The air motor (Model No LG30FT, requires a gas supply of 4248 cm$^3$/s) (TONSON, 2015) to drive the FFR which will be powered using CO$_2$ gas in situ generated from dry ice. The motor is driven by the generated volumetric flow rate and pressure of the gas. As a result, three parameters need to be determined: time for production of gas, the volume of CO$_2$ gas, and generated gas pressure. As the expected operating environmental condition for the robot is at low pressure and moderate temperatures, the volume and pressure can be computed using the ideal gas equation and the equation of sublimation of dry ice to CO$_2$ gas. Since time cannot be calculated from these equations, the SR of dry ice will be used to predict the time required when sufficient volume and pressure of the CO$_2$ gas is produced to drive the robot. Due to limited data on SRs of dry ice in the literature (Chevrier, Roe, White, Bryson, & Blackburn, 2008), an experimental approach will be used to determine the SR of dry ice using hot water.

This paper presents the investigation of the production rate of CO$_2$ gas from the dry ice with the objective of using the gas to power a FFR in a high-temperature fire environment. Since the gas is expected to be self-generated from dry ice within the FFR with high response time, hot water is proposed as a catalyst to speed up the production rate. An experimental approach will be developed to optimize the SR of CO$_2$ gas for constraint applications such as the mass of dry ice and water temperature. The outcome would be an optimal water temperature and mass of dry ice that will be used for the prototype development of a CO$_2$ gas propulsion system. The gas propulsion system would be used to drive an autonomous FFR operating in a high thermal indoor fire environment. The rest of this report is organized as follows: Section 2 examines the materials, methods as well as the design of experiments (DOEs). The results and analysis are discussed in Section 3, while the optimization analysis is presented in Section 4. The summary and conclusion are given in Section 5.

2. Materials and methods

2.1. Materials

The sample masses of dry ice for the experiment were in the range of 15–35 g (step increase of 5 g). Each sample used in this study was taken from the 5000-g blocks purchased from Linde Gas (The Linde Group,
Hot water at 60°C, 70°C, and 80°C was used for the experiment based on the realization reported in Ajala et al. (Ajala et al., 2016) that the SR below 60°C is negligibly small. Type-K Glass Braid Insulated–K thermocouple (with MAX31,855 breakout board amplifier) was used to measure the water temperature. Both the thermocouple and its amplifier were used with Arduino Uno board (UNO R3; based on the ATmega328 microcontroller) for data logging.

### 2.2. Experimental design

Statistical DOE is a method of designing a series of tests where the control variables (also known as control factors) are modified by a specified order to identify the reasons for the changes in the response parameters (Cavazzuti, 2012). There are various DOE techniques for experimental design, which include full-factorial design (FFD), response surface methodology (RSM), and Taguchi orthogonal array (TOA) method, among others. However, the choice of methods depends mainly on the aim of the experimentation (Cavazzuti, 2012). DOE is widely employed in many industrial and academic types of research for product and process design and/or optimization.

From our literature search, no studies have used dry ice to power a pneumatic motor, as well as use hot water to speed up the rate of sublimation of dry ice for the same purpose. So, this study employs a DOE technique using FFD and RSM approaches for design and optimizing CO₂ production rates for a FFR pneumatic actuation application. Figure 1 illustrates the process flowchart for the RSM statistical DOE employed in this study. The experimental approach is divided into three stages — planning stage, an execution stage, and analysis and optimization stage.

![Flowchart of the response surface method for experimental design and optimization.](https://doi.org/10.1080/23311916.2018.1555744)

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**1. Planning Stage**

- Start
- Response Variables Selection
  - $Y_1$: Sublimation Time
  - $Y_2$: Sublimation Rate
- Control Factors Selection
  - $x_1$: Water Temperature (3 levels)
  - $x_2$: Mass of Dry Ice (5 levels)
- Matrix Experiment Design
  - $L_{16}$ ($3^1 \times 5^2$) Full Factorial Design (FFD)
- Conduct Experiments
  - Laboratory experiments: Measure sublimation time & Compute sublimation rates

**2. Execution Stage**

**3. Analysis and Optimisation Stage**

- Fit Response Models
  - Linear and/or higher order models
  - $Y_1 = f(x_1, x_2)$
  - $Y_2 = f(x_1, x_2)$
- Analyse Data
  - ANOVA, p-values, R-squared etc.
- Model Fitness?
  - No
  - Yes
- Response Surface Analysis
  - Main effects plots
  - Probability/Residual plots
  - Response surface plots
- Design Optimisation
  - Determine constraints
  - Run optimisation analysis
- Optimal Operating Conditions
  - $Y_1 = f(X_1, X_2)_{opt}$
  - $Y_2 = f(X_1, X_2)_{opt}$
- End
2.2.1. Experimental planning
The planning stage consists of (a) the selection of the response variables as ST (Y₁) and SRs (Y₂); (b) the selection of the control factors as water temperature (X₁) and mass of dry ice (X₂). Three levels were selected for the water temperature and five levels for the mass of dry ice (see Table 1) to cover the experimental region. Upon the selection of response and design variables, the next step is the matrix experiment design.

With the levels of the control factors, we employed a $3^1 \times 5^1$ full-factorial design, thereby leading to a 15 run experimental (i.e., $L_{15}$) matrix (Table 2). Full-factorial design provides detailed information about the experimental design space. Hence, it is adjudged as a better choice in statistical experimental design (Barker & Milivojevich, 2016). However, full-factorial design becomes an expensive choice as the number of design factors increases. Nonetheless, with only two design factors involved in this study, the full-factorial design is considered adequate.

Table 1. Experimental control factors and their levels

<table>
<thead>
<tr>
<th>Factors</th>
<th>Units</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water temperature</td>
<td>°C</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 70 80</td>
</tr>
<tr>
<td>Dry ice mass</td>
<td>g</td>
<td>15 20 25 30 35</td>
</tr>
</tbody>
</table>

Table 2. $L_{15}$ ($3^1 \times 5^1$) FFD experimental design matrix

<table>
<thead>
<tr>
<th>Run</th>
<th>$X_1$ (°C)</th>
<th>$X_2$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>80</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>13</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>15</td>
</tr>
</tbody>
</table>
The container used for measurement is a transparent 1750 cm$^3$ jar. For each of the experimental trial shown in Table 2, the container is filled with 200 cm$^3$ of water, which was allowed to cool down to the desired temperature. After that, the desired sample mass of the dry ice is cut from a 5000-g slab dry ice, weighed, and recorded. The temperature of the cooling water was monitored with the thermocouple with the data displayed and logged on the personal computer. The moment the desired temperature is achieved the Arduino controller is reset with the aid of an onboard reset switch and the sample mass of dry ice is dropped into the 200 cm$^3$ water in the open container.

Furthermore, the temperature of water at the beginning and end of the sublimation of the dry ice were recorded. The sublimation of dry ice in hot water is then observed and the time ($Y_1$) for the sample mass to completely sublime is logged with the test equipment described earlier. This process is repeated for the experimental matrix presented in Table 2.

2.2.3. Experimental data analysis
For each of the ST ($Y_1$) obtained during each of the experimental trials, the SR ($Y_2$) was computed using Equation (1) as documented in the study of Murphy and McSweeney (2013). The sublimation rate is denoted by $SR$, mass by $m$, and time by $t$ in the equation. The experiments were conducted in a random order to limit the errors due to instrumentation and data collection procedures. Additionally, to further prevent inherent measurement errors the experimental runs were performed in triplicates, and the average presented.

$$SR = f(m, t)$$  \hspace{1cm} (1)

Response surface methodology (RSM) was used for the data analysis to examine the effect of water temperature and dry ice mass on the sublimation rates of dry ice. This is because RSM is suitable for continuous control factor (e.g., time, mass) and also when the objective is to optimize the response variable(s) of interest (Khoei, Masters, & Gethin, 2002). In the RSM approach, using the selected experimental data, a polynomial function was used to fit models that describe the relationship between the control factors and response variables. Equation (2) (Montgomery, 2001) shows the polynomial function that describes the relationship between the control factors and response variables.

$$Y = a_0 + \sum_{i=1}^{k} a_iX_i + \left( \sum_{i=1}^{k} a_iX_i \right)^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} a_{ij}X_iX_j + \epsilon$$  \hspace{1cm} (2)

where $Y$ represents the response, $a_0$ is the intercept; $a_i$ is the coefficient of linear factor effects, $a_{ij}$ is the interaction coefficient, $a_{ii}$ is the quadratic coefficients, and $\epsilon$ is the error terms. Upon the completion of data fitting, the next step in the data analysis is showing the main effects of the control factors. This is subsequently followed by the evaluation of the analysis of variance (ANOVA)
to validate the significance of the models and assess the relative importance of the control factors. ANOVA analysis involves the estimation of the sum of squares values from different factors. The experimental design and statistical analysis were conducted using Design-Expert® software (Stat Ease Inc., 2015). The model-fitting was tested regarding the coefficient of determination (i.e., \( R^2 \), Adjusted \( R^2 \), and Predicted \( R^2 \)) and the level of probability, i.e., \( p \)-values.

The validity of the RSM-fitted model to the experimental dataset is based on three assumptions: (a) that the treatment population be normally distributed, (b) the variance of the observation is each treatment be equal, and (c) the observation be randomly selected from the treatment population (Pan, 2016), (Khan, 2013). Thus, it is essential to conduct quality assurance checks on the experimental dataset to ensure the suitability of the RSM-fitted model to the data. The quality assurance consists of normality, constant variance, and independence tests, which are, respectively, conducted with normal probability plot of residuals, Residuals versus Fit plot, and Residual versus order plot. As such, this study developed and assessed the residual plots to ascertain the RSM application validity assumptions.

Having fitted the model and ascertain their validity, it is of interest in this study to know the best settings for the control factors. Hence, we carried out an optimization study to assess the control factors’ (i.e., water temperature, and mass of dry ice) settings that optimize the ST and SRs.

3. Results and discussion

3.1. Response analysis

Table 3 presents the experimental results for the two response variables, i.e., ST and SRs under different control factors (i.e., water temperature and mass of dry ice) settings. The response for the SR is in the range of 0.0718–0.1563 g/s, while that of the ST falls between 153.5–209 s. The experimental data were analyzed in order to measure temperature and mass effect on the sublimation of dry ice.

3.1.1. Model-fitting

Regression computations fitting all the polynomial models to the responses were performed to generate an acceptable model. The sequential model sum of squares and model summary statistic tests were applied for this purpose. The tests calculate the effects of all the model

<table>
<thead>
<tr>
<th>Run</th>
<th>X₁ (°C)</th>
<th>X₂ (g)</th>
<th>ST (s)</th>
<th>SR (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>35</td>
<td>283</td>
<td>0.1237</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>35</td>
<td>298.5</td>
<td>0.1173</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>15</td>
<td>209</td>
<td>0.0718</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>25</td>
<td>200</td>
<td>0.1250</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>15</td>
<td>176</td>
<td>0.0852</td>
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<tr>
<td>6</td>
<td>70</td>
<td>25</td>
<td>209</td>
<td>0.1196</td>
</tr>
<tr>
<td>7</td>
<td>80</td>
<td>35</td>
<td>224</td>
<td>0.1563</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>20</td>
<td>213.5</td>
<td>0.0937</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>30</td>
<td>251</td>
<td>0.1195</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>30</td>
<td>209</td>
<td>0.1435</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>25</td>
<td>257</td>
<td>0.0973</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>30</td>
<td>275.5</td>
<td>0.1089</td>
</tr>
<tr>
<td>13</td>
<td>80</td>
<td>20</td>
<td>190.5</td>
<td>0.1050</td>
</tr>
<tr>
<td>14</td>
<td>60</td>
<td>20</td>
<td>261</td>
<td>0.0766</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>15</td>
<td>153.5</td>
<td>0.0977</td>
</tr>
</tbody>
</table>

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https://doi.org/10.1080/23311916.2018.1555744
terms and the results are displayed in Tables (4, 5). From Table 4, a linear model is found as the most appropriate. This is because the linear model produces high F values of 103.22 for SR and 76.44 for ST, with corresponding low p-values (<0.0001).

Model summary statistics' result presented in Table 5 confirms the suitability of the linear model. This is because the model exhibits a low standard deviation (0.00594 and 12.18 for SR and ST, respectively), high $R^2$ values (0.9451 for SR and 0.9272 for ST), and a corresponding least value of predicted residual sums of squares (0.00064 for SR and 2735.32 for ST) for both the SR and ST. A reasonable agreement between the difference in the values of the Adjusted $R^2$ and Predicted $R^2$ (0.0186 for SR and 0.0269 for ST) is also observed from Table 5. This also validates the acceptance of the linear model because the reasonable difference should be lower than 0.2 (Montgomery, 2001).

$R^2$ indicates the amount of relationship of the response variable to the combined linear predictor variables. Therefore, the $R^2$ value of 0.9451 and 0.9271 (Table 5) implies that the model can explain more than 94% of the experimental data for the SR and 92% for the ST. The high value of the adjusted $R^2$ and Predicted $R^2$ is also an indication of a strong relationship between the observed and the predicted values.

3.1.2. Model adequacies
Following the satisfactory fitting result displayed from the model diagnosis above, a quality assurance test to check the normality of the data. This is displayed as a normal probability plot of residuals for the response variables in Figure 3. The distribution of the data around the half-normal plots (i.e., the straight line) in Figure 3(a,b) indicates that the residuals follow a normal distribution. Also, the scattering of the data randomly between the red lines in Figure 4(a,b) further confirms the assumption of constant variance and the absence of outliers. In other words, as the assumption of normality is satisfied, the model generally fits all the data well.

3.1.3. Mathematical model development
The mathematical relationship between the responses and the control factors in terms of the coded and actual values of the variables is presented in Equations (3)–(6). The coded equations

<table>
<thead>
<tr>
<th>Table 4. Sequential model sum of squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
</tr>
<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td>(a) Sublimation rate (SR)</td>
</tr>
<tr>
<td>Mean vs Total</td>
</tr>
<tr>
<td>Linear vs Mean</td>
</tr>
<tr>
<td>2FI vs Linear</td>
</tr>
<tr>
<td>Quadratic vs 2FI</td>
</tr>
<tr>
<td>Cubic vs Quadratic</td>
</tr>
<tr>
<td>Residual</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>(b) Sublimation time (ST)</td>
</tr>
<tr>
<td>Mean vs Total</td>
</tr>
<tr>
<td>Linear vs Mean</td>
</tr>
<tr>
<td>2FI vs Linear</td>
</tr>
<tr>
<td>Quadratic vs 2FI</td>
</tr>
<tr>
<td>Cubic vs Quadratic</td>
</tr>
<tr>
<td>Residual</td>
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<tr>
<td>Total</td>
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</tbody>
</table>
given in Equations (3) and (4) are useful for identifying the relative impact of the factors by comparing the factor coefficients. Thus, it can be deduced from Equations (3) and (4) that the mass of dry ice (coefficients of 0.0255 and 40.30) has a more significant effect on sublimation of dry ice than water temperature (coefficients of 0.016 and −32.40).

\[
Y_1 = +0.11 + 0.016X_1 + 0.0255X_2 \quad (3)
\]

\[
Y_2 = +227.37 - 32.40X_1 + 40.30X_2 \quad (4)
\]

where: \(Y_1\) = Sublimation rate (g/s); \(Y_2\) = Sublimation time (s); \(X_1\) = water temperature (°C), and \(X_2\) = dry ice mass (g).

The equation in terms of the actual values of the factors is shown in Equations (5) and (6). These equations are useful to predict the response for given levels of each of the control factors. These models are valid within the region of the experimental design, that is, the applied range of the experimental control parameters of this research.

\[
Y_1 = -0.063147 + 0.001556X_1 + 0.002545X_2 \quad (5)
\]

\[
Y_2 = 353.41667 - 3.24X_1 + 4.03X_2 \quad (6)
\]

Table 5. Model summary statistics

<table>
<thead>
<tr>
<th>Source</th>
<th>Std. Dev.</th>
<th>(R^2)</th>
<th>Adjusted (R^2)</th>
<th>Predicted (R^2)</th>
<th>PRESS</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) Sublimation rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>5.939 \times 10^{-3}</td>
<td>0.9451</td>
<td>0.9359</td>
<td>0.9173</td>
<td>6.371 \times 10^{-4}</td>
<td>Suggested</td>
</tr>
<tr>
<td>2FI</td>
<td>5.805 \times 10^{-3}</td>
<td>0.9519</td>
<td>0.9388</td>
<td>0.9251</td>
<td>5.773 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>Quadratic</td>
<td>6.19 \times 10^{-3}</td>
<td>0.9552</td>
<td>0.9304</td>
<td>0.8825</td>
<td>9.053 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>Cubic</td>
<td>5.245 \times 10^{-3}</td>
<td>0.9786</td>
<td>0.95</td>
<td>0.7905</td>
<td>1.614 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td><strong>(b) Sublimation time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>12.18</td>
<td>0.9272</td>
<td>0.9151</td>
<td>0.8882</td>
<td>2735.32</td>
<td>Suggested</td>
</tr>
<tr>
<td>2FI</td>
<td>12.51</td>
<td>0.9296</td>
<td>0.9104</td>
<td>0.874</td>
<td>3082.65</td>
<td></td>
</tr>
<tr>
<td>Quadratic</td>
<td>13.62</td>
<td>0.9317</td>
<td>0.8938</td>
<td>0.8253</td>
<td>4273.25</td>
<td></td>
</tr>
<tr>
<td>Cubic</td>
<td>11.27</td>
<td>0.9688</td>
<td>0.9723</td>
<td>0.6849</td>
<td>7706.69</td>
<td>Aliased</td>
</tr>
</tbody>
</table>

Figure 3. Normal plot of residuals for sublimation (a) Time response and (b) Rate response.
3.1.4. Analysis of variance (ANOVA) of the fitted model

The statistical significance of the linear model was estimated using the ANOVA technique, and the results are presented in Table 6. The ANOVA proved that the selected linear model is suitable (i.e., significant). This is due to the high $F$ value with a corresponding low $p$-value (<0.0001). Hence, the two factors Water Temperature ($X_1$) and Dry ice Mass ($X_2$) in Table 5 are regarded as significant model terms at a 95% confidence level.

3.2. Effects of control factors on the response variables

3.2.1. Contour and 3D surface plots

A 2D graphical representation of the relationship between the responses and the control factors is presented as contour plots in Figure 5(a,b) in order to visualize the control factors' effects. The plots demonstrate that both factors have an individual effect (i.e., the main effect) on both the ST and the SR. Thus, variation in the factors results in changes in the responses. The ST increased at higher masses of dry ice (Figure 5(a)), while Figure 5(b) revealed that a high SR is achieved by subliming large masses of dry ice at higher water temperature.

The linear variation effect becomes more visible with a three-dimensional (3D) surface plots shown in Figure 6(a,b). These plots indicated that there is no interaction effect of the mass of dry ice and the water temperature on both the ST and the SR. Figure 6(a) shows the effect of water temperature and dry ice mass on the ST. The results revealed that the ST is increasing as large masses of dry ice sublimes. It, however, decreases when the temperature increases. An increased SR is achieved at both higher dry ice masses and water temperature as indicated in Figure 6(b).

3.2.2. Main effect plots

The goal of this experiment is to study the influence water temperature on the different masses of dry ice such that volume requirement of CO$_2$ gas can be produced to satisfy the 4250 cm$^3$/s consumption rate of the selected pneumatic motor. Given this, a short time response for the gas production is desirable. To achieve this, the main effect plot using the data means was employed to study the influence of each of the factors (water temperature and mass of dry ice) on the SR and ST of dry ice. This is presented in Figures 7 and 8, respectively.

Figures 7 and 8 show the main effects of the control factors on the ST and SRs. Figure 7 provides the effects of water temperature on both the SR (Figure 7(a)) and ST (Figure 7(b)) of dry ice. The linearly increasing relationship shown in Figure 7(a) suggests that the water temperature aid the SRs, with the highest SR of 0.1563 g/s recorded at the highest...
temperature (80°C). The result is consistent with findings of Winkel (2012) and Kochtubajda & Lozowski (1985) that sublimation is faster in a warm environment. Also for every 10°C rise in temperature, about 0.016 g of dry ice sublimes in 1 s. Figure 7(b), however, indicates that ST decreases for every increase in temperature. The highest temperature (80°C) resulted in a minimum ST of 153.5 s. Similar to SRs, the ST is reduced by 32.4 s for every 10°C rise in temperature. These two conditions are desirable for the present study.

The mass effect plot in Figure 8(a) also produces a high SR as the dry ice mass increases. This is consistent with the findings that high mass of dry ice produces a high concentration of CO₂ gas (i.e., the high volume of the gas). Conversely, the high volume (produced at 80°C,

Table 6. ANOVA for the response surface of the linear model

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F value</th>
<th>p-value Prob &gt; F</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Sublimation rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>7.28 x 10⁻³</td>
<td>2</td>
<td>3.64 x 10⁻³</td>
<td>103.22</td>
<td>&lt;0.0001 Significant</td>
<td></td>
</tr>
<tr>
<td>X₁</td>
<td>2.421 x 10⁻³</td>
<td>1</td>
<td>2.421 x 10⁻³</td>
<td>68.65</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>X₂</td>
<td>4.859 x 10⁻³</td>
<td>1</td>
<td>4.859 x 10⁻³</td>
<td>137.78</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>4.232 x 10⁻⁴</td>
<td>12</td>
<td>3.527 x 10⁻⁵</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor total</td>
<td>7.703 x 10⁻⁵</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Sublimation time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>22,678.27</td>
<td>2</td>
<td>11,339.14</td>
<td>76.45</td>
<td>&lt;0.0001 Significant</td>
<td></td>
</tr>
<tr>
<td>X₁</td>
<td>10,497.6</td>
<td>1</td>
<td>10,497.6</td>
<td>70.77</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>X₂</td>
<td>12,180.68</td>
<td>1</td>
<td>12,180.68</td>
<td>82.12</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>1779.96</td>
<td>12</td>
<td>148.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor total</td>
<td>24,458.23</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
35 g, 0.5678 g/s) comes with a time constraint. At this factors’ combination, the long ST of 224 s as indicated in Figure 8(b) will lead to delay in the actuation of the FFR, which is undesirable. The deduction from Figure 8(a) has been the strength of the majority of the earlier studies cited on the SRs of dry ice to generate CO₂ gas in the introduction section. They focus on creating a large volume of the gas from dry ice giving preference to the volume of the gas only. As such, short time of sublimation for the gas production along with the method of achieving the short time response becomes less critical due to their application areas.

A consideration for the size of the dry ice can also be a useful design criterion in addition to the use of hot water to achieve the short time of sublimation because the dry ice SR is proportional to its size (Winkel, 2012). Also optimizing the SR alone without proper consideration for dry ice mass will delay the achievement of the required gas volume in FFR consideration. In the FFR application, the two parameters (water temperature and dry ice mass) as well the SR are essential. This is because high response time (i.e., short time of sublimation) is required for the dry ice sublimation of the CAFFR suggested in our earlier study (Ajala et al., 2016). Implementing this will make the CAFFR to operate successfully inside an indoor fire when the fire has already started. Results from Figures 7 and 8 when taken together suggest the need to optimize the SR and other parameters.

4. Parametric optimization
The aim of this study is to determine the maximum water temperature that will accelerate sublimation of a given mass of dry ice in minimal time and produce an optimum SR in order to achieve the flow requirement of the air motor. Thus, the optimization component in Design-Expert® 9 (Stat Ease Inc., 2015) was adopted.

4.1. Optimization criteria with solution
The SR is maximized and set to the highest level of importance. Also, the water temperature is maximized, whereas both the ST and mass of dry ice are minimized thereby set to the same
level of importance. Solutions are then found using numerical optimization node. The result obtained from the optimization is displayed in Figure 9. The solution that came out as the optimum for the SR, water temperature, mass of dry ice, and ST is 0.1025 g/s, 80°C, 16.1683 g, and 159.375 s, respectively, with a desirability 0.923. The 3D plot of the desirability of the optimization is given in Figure 10. Also, the 3D plot for the optimal SR and ST are displayed in Figures 11 and 12, respectively.

5. Conclusion
This study examined the effect of water temperature on the SRs of different masses of dry ice. During this investigation, the DOEs based on response surface methodology was utilized to optimize the SR and ST based on water temperature and mass of dry ice. This is done in
order to predict the production rate of CO\textsubscript{2} from dry ice along with the pressure requirement of a pneumatic motor for pneumatic power generation. Hot water at 60°C, 70°C, and 80°C were used to accelerate the sublimation of dry ice. The obtained results have indicated that higher water temperature will increase the SR and decrease ST which is necessary for the quick response of the actuator. Also, increasing the dry ice mass will increase ST. Hence, the best approach is to minimize ST in order to generate quick pressure response. An optimal SR
value of 0.1025 g/s is obtained at a temperature of 80°C, mass of 16.1683 g, and ST of 159.375 s. Results obtained in this investigation provide a solid foundation for the optimization of CO₂ SR in the generation of the gas pressure required to power a pneumatic motor. It will also be used as the basis for the completion of the prototype development. Although the pneumatic motor, in this study, will be used to propel a FFR in the high thermal indoor fire, the same approach is applicable in other highly constrained applications. The approach is scalable as more factors (e.g., container insulation that is assumed to be constant in the current study) can be included for further optimization.

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References


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