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# MATHEMATICAL MODELS FOR THE PREDICTION OF THE EFFECTS OF CARBON-MONOXIDE ON HUMAN HEALTH UNDER CONTINUOUS AND PERIODIC EXPOSURES

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**Abstract:** The rapid increase in technological innovations and utilizations have adversely affected the environment and consequently continued to threat future survival of human. To counter these assaults of the resultant environmental pollution and the threats of further degradation of the environment, the basic recommended approach for predicting the impact of the pollution and for the determination of the risk assessment strategies is through the use of mathematical models. Therefore, this paper presents mathematical models for the computations of carbon monoxide and carboxylhaemoglobin (COHb) in the blood for the cases of human under continous and periodic exposures to the pollutant. Using the percentage of COHb in the blood as a good index of health effects of carbon-monoxide (CO) on humans, the computed COHb from the developed models is used to predict the effects of CO on human health. On the validation of the developed models, the computed results show good agreement with experimental results. This work will assist in evaluating the technological injuries, effectively controlling our pollutants emissions and also as a tool for designing and developing better equipments and engines with lower emissions.

**Keywords:** Mathematical Models, Carbon-monoxide, Carboxyhaemoglobin, Human Health Effects

## 1. INTRODUCTION

The deterioration of environmental quality began with the congregating of mankind into groups, such as, hamlets, villages etc. and became serious problem since the industrial revolution. In the second half of the twentieth century, under the ever-increasing impacts of the exponentially growing population and of the industrializing society, environmental contamination of the air, water, soil and food steadily became a threat to the very survival of the human race. Understandably, many signified industrial and governmental communities have recently committed large resources of money and human power to the problem of environmental pollution and pollution abatement by effective control measures focusing on achieving air quality standard in accordance with the Clean Air Act of 1967 [1]. However, resolving the problems, one must predict the ambient air concentrations that will result from any planned set of emissions. According to El-Harbawi *et al.* [2], mathematical models are extremely useful tools to predict the impacts of chemical process accidents. Developing such models will drastically reduce the cost and the task associated with experimentations, as an alternative way of determining the effects of the pollutants.

Following the increase in vehicular traffic and rapid industrialization, carbon-monoxide (CO) is considered as a common atmospheric pollutant that directly affects human health (Singh *et al.*, [3]). The adverse effects of this pollutant have aroused the interest of many researchers to study the emission and the degree of the effects of the pollutant on human health. In earlier works, Coburn *et al.* [4] and Latiies [5] pointed out the effects of relatively small CO exposures, which are normally found in urban, industrial and household air while in the recent times, Gallagher and Mason [6] presented a study on carbon monoxide poisoning in two workers using an LPG forklift truck within a cold store. As part of their findings, the clinical assessment with mathematical exposure modelling may lead to successful retrospective diagnosis of CO poisoning and identify putative work activities. Moreover, the CO poisoning should be suspected whenever internal combustion engines are used within buildings and workers complain of relevant symptoms. From the biological investigations, correlation was found to exist between environmental pollution and Hepatitis, hence conclusions were reached that several disease processes involve factors of environmental pollution, such as, the direct effects of pollution on lungs involving lung diseases and indirect effects on all parts of the body. The adverse effect of air pollution on health was further corroborated by Ren and Tong [7]. Providing solutions or finding a way to abate the problems if not totally eliminated, has been the ultimate purpose of most concerning researchers. One way of establishing a solution is the fact that CO inhibits the blood's capacity to carry oxygen. Since, hemoglobin has as much as

200 times affinity for CO as readily as Oxygen, when inhaled, it binds reversibly with blood hemoglobin to form carboxyhemoglobin, impairing the oxygen-transport capacity of the blood, as well as the oxygen's release to body tissues. Therefore, the percentage of COHb in the blood has been considered as a good index of health effects of CO on humans [8]

As pointed out by El-Harbawi *et al.* [1], the development of mathematical models for the computation of percentage COHb in due blood has been used to predict the impacts of the pollutant on human health. In the earlier work, Forbes *et al.* [9] proposed the formulae to compute COHb level in the blood as a function of exposure time by measuring the rate of CO uptake by humans under a wide range of conditions. Also, Forster *et al.* [10] derived an equation containing 14 parameters to predict the COHb level in the blood while Coburn *et al.* [4] later developed a model for the relationship between blood COHb, rate of CO production and the respiratory CO exchange. In the model, a constant concentration of $O_2Hb$ in the blood was assumed based on the linearized nature of the developed equation. However, Peterson and Stewart [11] pointed out that the constant value of $O_2Hb$ in the Coburn *et al's* equation (CFK equation) led to a significant error in the computation of blood COHb. Therefore, they proposed an iterative procedure for accounting the variation of $O_2Hb$ in the CFK equation. The nonlinear CFK equation was solved numerically by Bernard and Duker [12] equation using the fourth order Runge Kutta method while in the same year, Tyuma *et al.* [13] obtained an analytical solution of the CFK equation while assuming that hemoglobin is always saturated with $O_2$ or CO or both. Also, Collier and Goldsmith [14] adopted the method proposed by Roughton and Darling [15] to solve the CFK equation by taking into consideration the reduced haemoglobin. Although the CFK equation was developed for the prediction of the concentration of CO in the body, it has been widely used to predict blood COHb under different CO exposures (Weir and Viano [16]; Marcus [17]; Tikuisis *et al.* [18], Wallace *et al.* [19]). More than three decades ago, Ott and Mage [20] and Venkatram and louch [21] proposed linear models for the computation of the percentage COHb in the blood.

The above reviewed developed models are based on empirical laws and which are do not appear to be derived from the basic physical principles. In developing the mathematical models that are based on physical principles, a great deal of complexities arises both in the solution and the involving parameters. It should therefore be noted that, the quest for the development of simple mathematical models for the computation of CO and COHb in the blood has been on. Consequently, the objective of this work is to develop simple mathematical models that can predict the effects of the accumulation of the pollutant on human health as a function of exposure time and the ambient pollutant concentration. This will serve as a way of evaluating our technological injuries, effectively controlling our pollutants emissions and also as a tool for designing and developing better equipments and engines with lower emissions.

## 2. THEORETICAL BACKGROUND

The effects of various pollutants on human health are shown in Figure 1 below. In the pool of these health-damaging pollutants, an air pollutant called carbonmonoxide is considered as a common pollutant that directly affects human health as it also produces change in human physiology. Considering the source of this pollutant, it is actually a product of incomplete combustion of hydrocarbon-based fuel, which becomes toxic when inhaled by man due to the strong affinity of haemoglobin (Hb), the oxygen carrier of the blood. Since, the hemoglobin has as much as 200 times affinity for CO as readily as Oxygen, when inhaled, it binds reversibly with blood hemoglobin to form carboxyhemoglobin, impairing the oxygen-transport capacity of the blood, as well as the oxygen's release to body tissues, causing loss of consciousness, fatal asphyxiation, brain damage and all other kinds of health effects as shown in Table 1 below. Death occurs in human exposed to concentration of around 1000 ppm, corresponding to blood levels of 60% COHb. Reasonably, correlations have been found between daily mortality levels and CO. In addition, heart function has been shown to be altered by elevated COHb, as evidenced by the electrocardiograms of exposed healthy adults.

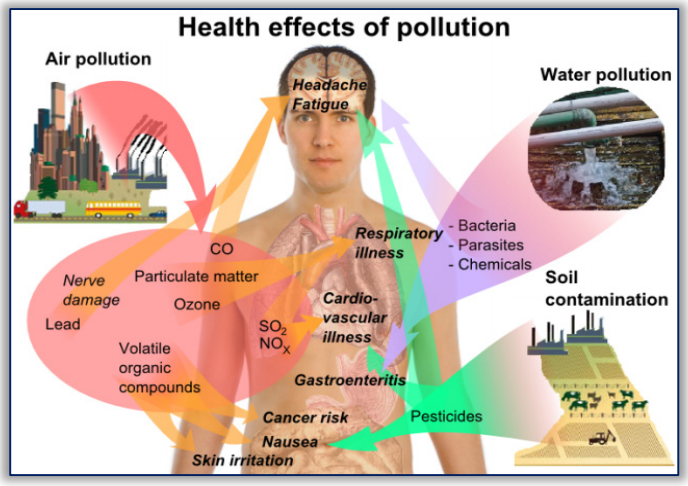


Figure 1. Overview of main health effects on humans from some common types of pollution

Table 1: Effects of *Carboxylhaemoglobin (COHb)* in the blood on Human health. Source: Nevers [22]

| Percentage of carboxylhaemoglobin (COHb) in the blood | Effect |
|---|---|
| 0.3-0.7 | Physiologic norm for nonsmokers |
| 2.5-3.0 | Cardiac function decrements in impaired individuals, blood flow alterations; and, after extended exposure, changes in red blood cell concentration. |
| 4.0-6.0 | Visual impairments, vigilance decrements, reduced maximal work capacity |
| 3.0-8.0 | Routine values in smokers. Smokers develop more red blood cells than nonsmokers to compensate for this, as do people who live at high elevations, to compensate for the lower atmospheric pressure. |
| 10.0-20.0 | Slight headache, lassi-breathlessness from exertion, dilation of blood cells in the skin, abnormal vision, potential damage to foetuses. |
| 20.0-30.0 | Severe headaches, abnormal manual dexterity. |
| 30.0-40.0 | Weak muscles, nausea, vomiting, dimness of vision, severe headaches, irritability, and impaired judgment. |
| 50.0-60.0 | Fainting, convulsions, coma |
| 60.0-70.0 | Coma, depressed cardiac activity and respiration, sometimes fatal |
| >70.0 | Fatal |

## 3. DEVELOPMENT OF THE MATHEMATICAL MODELS

As reported by Coburn and Forman [23], the blood COHb in the body is determined by the exchange of CO between the pulmonary capillary blood and the ambient air, endogenerous production of CO, dilution of CO in the body tissue and metabolic consumption of CO, while the ambient air is transported to alveoli by ventilation. The blood then absorbs the CO from alveoli when it passes through the pulmonary capillaries.

In this section, simple mathematical models developed for the computation of percentage COHb in the human blood for the subject exposed to permanent constant flux of atmospheric pollution.

Applying the principle of continuity,

$$V\frac{dC_{CO}}{dt} = F_1 b C_a - \left(F_2 b + F_3 k\right)C_{CO} \tag{1}$$

The above Eq. (1) can be written as

$$V\frac{dC_{CO}}{dt} + \left(F_2 b + F_3 k\right)C_{CO} = F_1\ b\ C_a \tag{2}$$

On solving the differential Equ. (2) using Laplace transform, one arrives at

$$C_{CO} = \left[\frac{F_1 b C_a}{F_2 b + F_3 k}\left(1 - e^{-\frac{(F_2 b + F_3 k)t}{V_b}}\right) + C_o e^{-\frac{(F_2 b + F_3 k)t}{V_b}}\right] \tag{3}$$

It should be noted that

$$as\ t \to \infty,\ F_1 b \to F_2 b + F_3 k \qquad C_{CO} \to C_a$$

For the subject with an occupational exposure to constant atmospheric pollutant at regular intervals of T, this is captured by Equ. (4) as

$$C_{CO} = \left[\frac{F_1 b C_a}{F_2 b + F_3 k}\left(e^{\frac{(F_2 b + F_3 k)T}{V_b}} - 1\right)e^{-\frac{F_2 b + F_3 k}{V_b}(t-(n-2)T)} + C_o\, e^{-\left(\frac{(F_2 b + F_3 k)t}{V_b}\right)} \sum_{n=1}^{N} e^{-\frac{F_1 b + F_2 k}{V_b}(n-1)T}\right] \tag{4}$$

From the International Committee for Standardization in Haemology, we have

$$\%\ COHb = \frac{C_{CO}}{Hb \times 1.398} \tag{5}$$

The expression for a subject exposed to permanent constant flux of the pollutant for a time, t, is

$$\%\ COHb = \frac{1}{Hb \times 1.398}\left[\frac{F_1 b c_a}{F_2 b F_3 k}\left(1 - e^{-\left(\frac{(F_2 b + F_3 k)t}{v}\right)}\right) + C_0\, e^{-\left(\frac{(F_2 b + F_3 k)t}{v}\right)}\right] \times 100 \tag{6}$$

Similarly, for the subject with an occupational exposure to the constant atmospheric pollutant at regular intervals of time, T, equ. (7) was developed.

$$\%CoHb = \frac{1}{Hb\times 1.398}\left[\frac{F_1\, b\, c_a}{F_2\, b + F_3\, k}\left(e^{\frac{(F_2 b+F_3 k)T}{V_b}} - 1\right)e^{-\frac{F_2 b+F_3 k}{V_b}(t-(n-2)T)} + C_o\, e^{-\left(\frac{(F_2 b+F_3 k)t)}{V_b}\right)}\sum_{n=1}^{N} e^{-\frac{F_1 b+F_2 k}{V_b}(n-1)T}\right]\times 100 \quad (7)$$

With the aim of simplifying the model for ease of computation, some factors are developed for the conversion of CO content in the blood to percentage COHb within the range of 1- 4 hours of exposure to atmospheric CO. These conversion factors as shown in Table 2 can be used instead of Eq. (5). Thus, Eq. (6) and (7) could be written as Equs. (8) and (9).

$$\%\ CoHb = \alpha\left[\frac{F_1\, b\, c_a}{F_2\, b\, F_3\, k}\left(1 - e^{-\left(\frac{(F_2\, b + F_3\, k)t}{V_b}\right)}\right) + C_o e^{-\left(\frac{(F_2\, b + F_3\, k)t)}{V_B}\right)}\right] \quad (8)$$

$$\%CoHb = \alpha\left[\frac{F_1\, b\, c_a}{F_2\, b + F_3\, k}\left(e^{\frac{(F_2\, b + F_3\, k)T}{V_b}} - 1\right)e^{-\frac{F_2 b+F_3 k}{V_b}(t-(n-2)T)} + C_o\, e^{-\left(\frac{(F_2\, b + F_3\, k)t)}{V_b}\right)}\sum_{n=1}^{N} e^{-\frac{F_1 b+F_2 k}{V_b}(n-1)T}\right] \quad (9)$$

Osgood [24] presented the variation of volume of blood as a function of sex and body weight of the subject as

$$V_b = \frac{m_b}{13} \qquad \text{for male} \quad (10a)$$

$$V_b = \frac{m_b}{15} \qquad \text{for female} \quad (10b)$$

while,

$$V_b = \begin{cases} 0.071 m_b & 15\ \text{years} \\ 0.075 m_b & 10\ \text{years} \\ 0.080 m_b & 1-6\ \text{years} \end{cases} \quad (10c)$$

## 4. RESULTS AND DISCUSSION

Using the initial percentage of COHb of 0.25% (Singh, [2]), Figure 2 shows the effects of breathing rate on the percentage concentration of COHb in human subject exposed to a constant concentration flux of 36.9 ppm of ambient CO for a maximum period of 1 hour. From the figure, 1.62 - 1.70 % of the COHb was predicted for breathing rates of 5 – 8 L/min.

Table 2: Conversion Factors from CO to %COHb

| Time (hr) | Ambient Concentration (ppm) 0-50 | 50-100 | 100-200 |
|---|---|---|---|
| 1 | 0.0475 | 0.0350 | 0.0300 |
| 2 | 0.0600 | 0.0550 | 0.0525 |
| 3 | 0.0800 | 0.0750 | 0.0700 |
| 4 | 0.1000 | 0.0800 | 0.0800 |

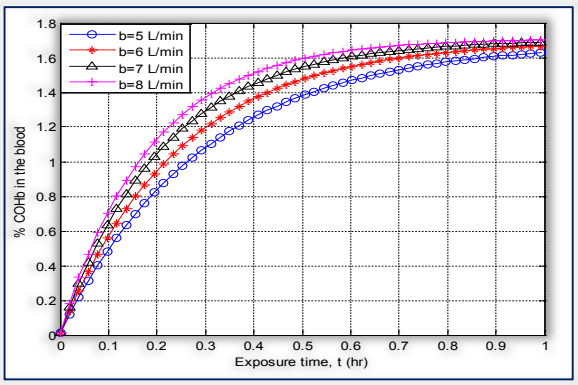


Figure 2. Effect of breathing rate on the Percentage of COHb in human subjects exposed36.9 ppm ambient CO for 1hr

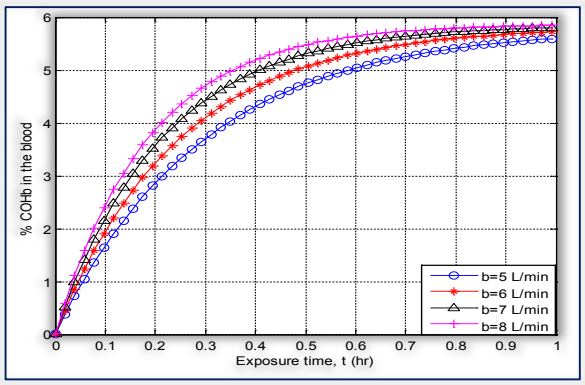


Figure 3. Effect of breathing rate on the Percentage of COHb in human subjects exposed constant concentration flux of constant concentration flux of 200.8 ppm ambient CO for 1hr

The subject exposed to a constant concentration flux of 200.8 ppm of ambient CO under the same exposure time depicts an increase in percentage of COHb to a maximum of 5.82 % for the breathing rates 8 L/min (Fig. 3). It could be inferred from the Figures that the percentage of COHb in human subjects increases with increase in the concentration of ambient CO and the breathing rates. Following the Table 1, the subject will experience visual impairments, vigilance decrements and reduced maximal work capacity.

Figs. 4 and 5 reveals the effects of breathing rates on the percentage of COHb in human subjects exposed to constant concentration fluxes of 44.7 ppm and 196.9 ppm ambient CO respectively , for a period of 2 hours. For these exposures, the percentage of COHb is between 2.5-10.0 %. Therefore, the subject will experience

slight headache, lassi-breathlessness from exertion, dilation of blood cells in the skin, abnormal vision, and potential damage to foetuses.

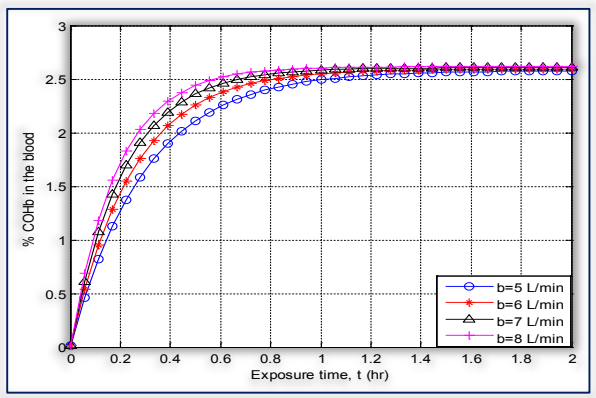


Figure 4 Effect of breathing rate on the Percentage of COHb in human subjects exposed flux of 44.7 ppm ambient CO for 2hrs

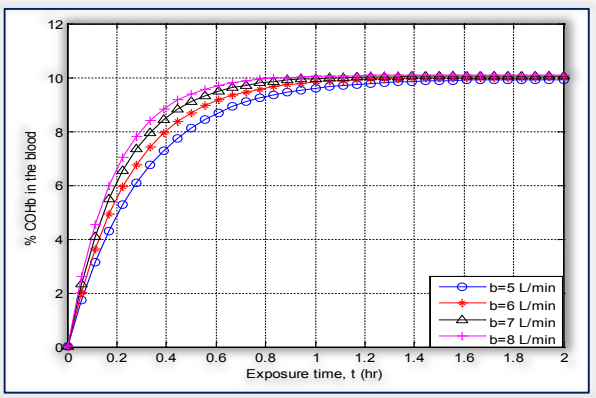


Figure 5. Effect of breathing rate on the Percentage of COHb in human subjects exposed constant concentration constant concentration flux of 196.9 ppm ambient CO for 2hrs

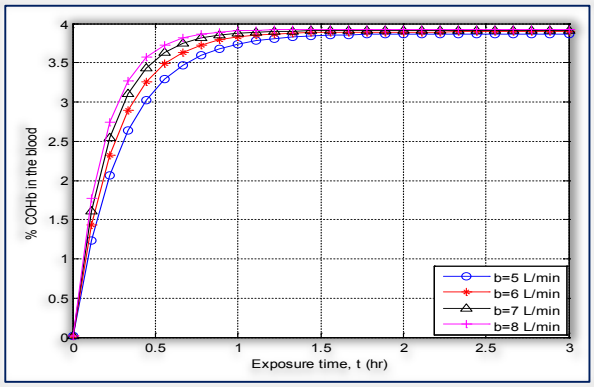


Figure 6. Effect of breathing rate on the Percentage of COHb in human subjects exposed flux of 46.0 ppm ambient CO for 3 hrs

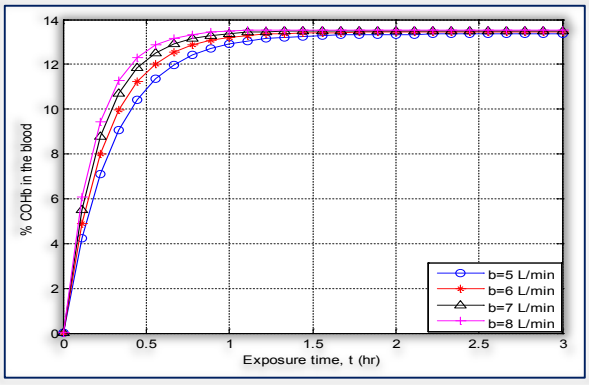


Figure 7. Effect of breathing rate on the Percentage of COHb in human subjects exposed constant concentration constant concentration flux of 198.4 ppm ambient CO for 3 hrs

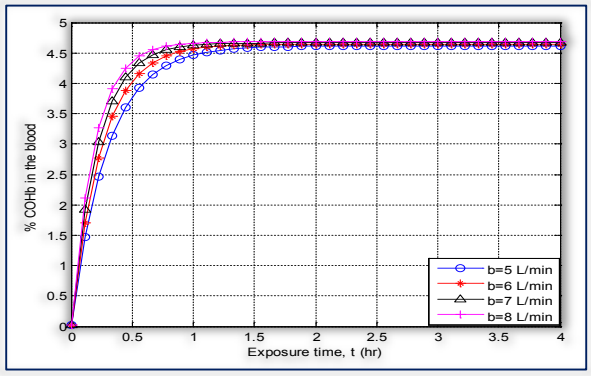


Figure 9. Effect of breathing rate on the Percentage of COHb in human subjects exposed flux of 48.0 ppm ambient CO for 4 hrs

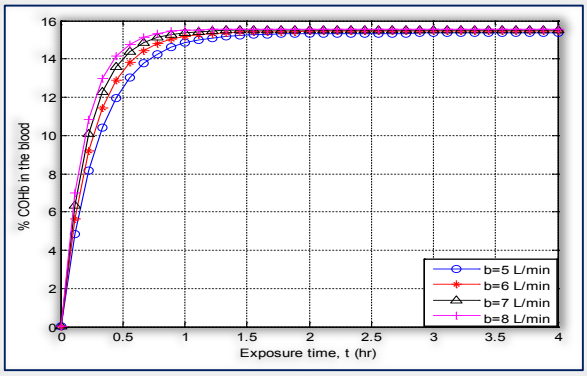


Figure 10. Effect of breathing rate on the Percentage of COHb in human subjects exposed constant concentration constant concentration flux of 199.5 ppm ambient CO for 4 hrs

The effects of breathing rate on the percentage concentration of carboxylheamoglobin (COHb) in human subject exposed to a constant concentration fluxes of 46.0, 198.4, 48, 199.5 ppm of ambient CO for periods of 3 and 4 hours are shown in Figs. 6, 7, 8 and 9 while Figs. 10 and 11 depict the effects of blood volume on the percentage concentration of carboxylheamoglobin (COHb) in human subject exposed to a constant concentration fluxes of 36.9 ppm and 200.8 ppm of ambient CO for a maximum period of 1 hour. The variations in blood volume correspond to the variation in the ages and amounts of blood in the subjects. The figures reveal that the percentage of COHb in human subjects increases with increase in the concentration of ambient CO and decreases with the subject's blood volume. The effects of elimination rates and breathed fractions of atmospheric pollutant on the percentage of COHb in human subject exposed to constant concentration flux

of 199.5 ppm ambient CO for 1hr are shown in Figs. 13 and 14. The figures describe that the percentage of COHb in human subjects decreases with increase elimination rates and increases with increase in the breathed fractions of atmospheric pollutant.

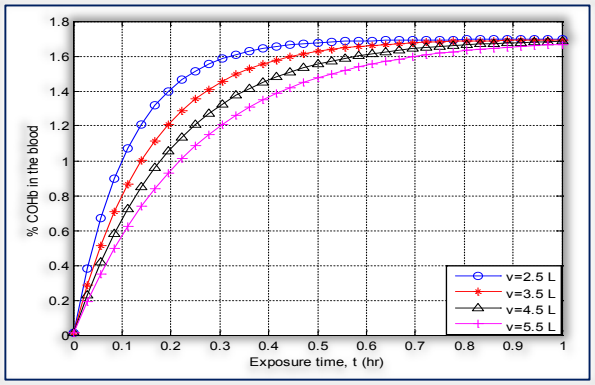


Figure 11. Effect of volume of blood on the Percentage of COHb in human subjects exposed 36.9 ppm ambient CO for 1hr

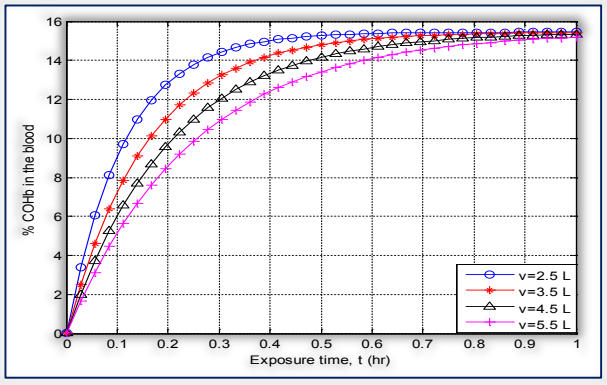


Figure 12. Effect of volume of blood on the Percentage of COHb in human subjects exposed constant concentration flux of constant concentration flux of 200.8 ppm ambient CO for 1hr

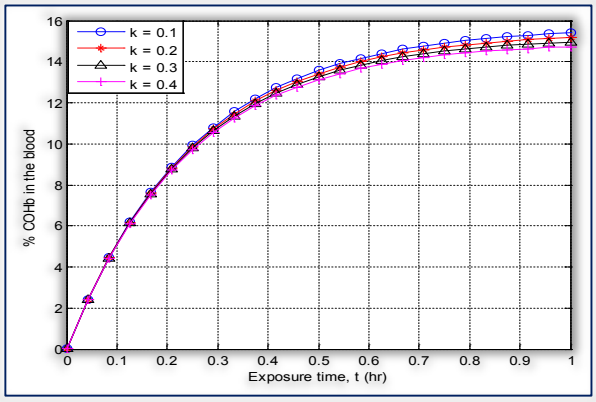


Figure 13. Effect of elimination rate on the Percentage of COHb in human subjects exposed flux of 199.5 ppm ambient CO for 1hr

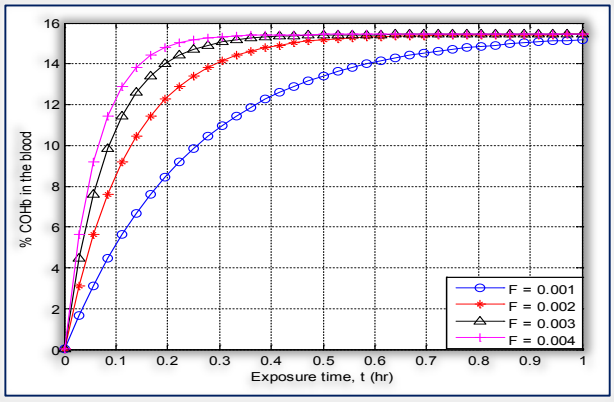


Figure 14. Effect of breathed fraction of atmospheric pollutant on the Percentage of COHb in human constant concentration subjects exposed constant concentration flux of 199.5 ppm ambient CO for 1hr

Since, the percentage of COHb in human subject increases with exposure time and the ambient CO, a subject expose to higher concentrations of CO for a prolong period of time will definitely experience severe headaches, abnormal manual dexterity, weak muscles, nausea, vomiting, dimness of vision, severe headaches, irritability, and impaired judgment, fainting, convulsions, coma, depressed cardiac activity and respiration. As the exposure continues under an increased concentration of ambient CO, the effects of the pollutant will be intensified and severe damage to the subject's health will result. In fact, deaths result when the percentage of COHb in human subject exceeds 70%. Tables 3-6 show the comparison of results and from the results analysis, the computed results in this study show good agreement with experimental results as also shown by Singh *et al.* [3].

Table 3: Comparison and Analysis of Results of Percentage COHb in the blood for 1 hr exposure to CO

| Ambient concentration (ppm) | Experimental results (Peterson and Stewart) | Singh et al Model | The Present Model |
|---|---|---|---|
| 36.9 | 1.80 | 1.69 | 1.72 |
| 51.6 | 2.12 | 2.00 | 2.24 |
| 87.9 | 2.90 | 2.96 | 2.97 |
| 93.5 | 3.37 | 3.11 | 3.16 |
| 200.8 | 5.93 | 5.93 | 5.82 |
| Standard Deviation | | 1.52 | 1.42 |

Table 4: Comparison and Analysis of Results of Percentage COHb in the blood for 2 hrs exposure to CO

| Ambient concentration (ppm) | Experimental results (Peterson and Stewart) | Singh et al Model | The Present Model |
|---|---|---|---|
| 25.4 | 1.50 | 1.78 | 1.47 |
| 44.7 | 2.48 | 2.71 | 2.60 |
| 96.4 | 5.10 | 5.20 | 5.13 |
| 196.9 | 10.08 | 9.98 | 10.00 |
| Standard Deviation | | 3.18 | 3.28 |

## 5. CONCLUSION

In this study, mathematical models for the variation of carbon-monoxide and carboxyl hemoglobin (COHb) in the blood have been developed. The models were used to compute the percentage of COHb in the human subjects. The computed COHb from the developed models was used to predict the effects of carbon-monoxide (CO) on human health.

The predicted results show good agreement with those measured experimentally (Peterson and Stewart, [10]) and the models developed by (Singh *et al*. [3]).

The variations in the models parameter indicate significant variations in the results. This can be used as a means of controlling the effects of the pollutant on human health.

Table 5: Comparison and Analysis of Results of Percentage COHb in the blood for 3 hrs exposure to CO

| Ambient concentration (ppm) | Experimental results (Peterson and Stewart) | Singh et al Model | The Present Model |
|---|---|---|---|
| 46.0 | 3.86 | 3.54 | 3.56 |
| 51.2 | 3.75 | 3.88 | 3.96 |
| 91.9 | 6.61 | 6.56 | 6.67 |
| 98.1 | 7.23 | 6.97 | 7.12 |
| 99.2 | 7.02 | 7.04 | 7.20 |
| 198.4 | 13.83 | 13.41 | 13.44 |
| Standard Deviation | | 3.24 | 3.23 |

Table 6: Comparison and Analysis of Results of Percentage COHb in the blood for 4 hrs exposure to CO

| Ambient concentration (ppm) | Experimental results (Peterson and Stewart) | Singh et al Model | The Present Model |
|---|---|---|---|
| 48.0 | 5.07 | 4.33 | 4.64 |
| 98.4 | 7.34 | 8.37 | 7.62 |
| 199.5 | 15.97 | 16.16 | 15.44 |
| Standard Deviation | | 4.91 | 4.55 |

### Nomenclature

n - Number of days of exposure.
V - Volume of blood in human body (L)
k - Net rate or elimination mechanism (Or removal rate) other than air exchange rate (L/min).
b - Rate of breathing or air exchange rate (Lit air/ air).
$C_a$ - Atmospheric Concentration of carbon monoxide, ppm
$C_{CO}$ - Concentration of carbon monoxide in the blood, ppm
$C_{COHb}$ - Concentration of carboxylheaomoglobin in the blood.
$C_o$ - Initial concentration of carbon monoxide content in the blood, ppm
$F_1$ - Fraction of the atmospheric pollutant that is breathed in or taken in through the nose
$F_2$ - Fraction of the atmospheric pollutant that is breathed out of the nose
$F_3$ - Fraction of the atmospheric pollutant that is removed through the elimination mechanism

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