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NUMERICAL ANALYSIS ON TRANSIENT THERMAL BEHAVIOUR OF CHARCOAL FILTERS IN NUCLEAR POWER PLANTS

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ABSTRACT

A number of radioactivity management features exist in the current generation Indian PHWRs that helps in reducing radioactivity concentration within the containment during normal as well as under accident conditions. These systems employ charcoal filters for the removal of airborne organic iodides in containments. These filters would be exposed to different flow rates, iodine concentration; during operation leading to higher temperatures. The temperature transients in these filters during filtration process are important from safety point view. For safety assessment, a numerical model based on finite difference was developed that can predict the temperature variations in charcoal bed under various operating conditions. Parametric studies have been conducted w.r.t flow rate and iodine concentration. The details of numerical model and the studies carried out are presented in this paper.

NOMENCLATURE

M : Mass (kg)
ρ : Density (kg/m^3)
C_p : Specific heat (J/kg.K)
K : Thermal conductivity (W/m.K)
T : Temperature (K)
h : Heat transfer coefficient (W/m^2.K)
A : Cross-section area (m^2)
t : Time (s)
x : Filter thickness (m)
V : Velocity (m/s)
θ : Porosity
c : Iodine concentration (mg/m^3)
λ : Decay constant (day^{-1})
Q : Heat (W)

Subscripts

c : Charcoal
a : Air
I : Iodine
d : Decay heat
L : Filter thickness

1. INTRODUCTION

The radioactivity management features of the reactor building are intended to remove gaseous fission products, mainly radioactive iodine in case of an accident [1]. These systems contain HEPA, roughing filter and charcoal filter etc. HEPA and roughing filters are intended for removing particulate matter and large size matter. These systems come into play under plant accident conditions and at that time they need to perform the radioactivity removal function. Thus, it is important to assess the performance of these filters under accident conditions. The transient temperature raise in these filters is one of the concerns which influence the filter performance.

In the present paper a numerical model based on finite difference is presented for predicting the temperature transients in charcoal filter under various operating conditions. Governing differential equations for charcoal bed and flowing air are presented. Realistic flow conditions and properties are given as inputs. Parametric studies were conducted w.r.t air flow and iodine concentration. The details of the mathematical model and results are discussed in the following sections.

2. MATHEMATICAL MODEL

The mathematical model consists of governing differential equation for energy balance over the charcoal bed and the air flowing through the charcoal filter. Charcoal filer is a porous material with fixed porosity and dimensions. A charcoal filter of square cross-section of 0.5m*0.5m with a length of 0.5m was considered for the study, as shown in Fig 1. The geometry, assumptions, mathematical expressions and boundary conditions are explained below.
Assumptions

- Charcoal Filter considered as a uniform porous media with filtration efficiency of 99%.
- The effect of charcoal temperature on filtration efficiency is neglected.
- Air flow rate is uniform throughout the filter.

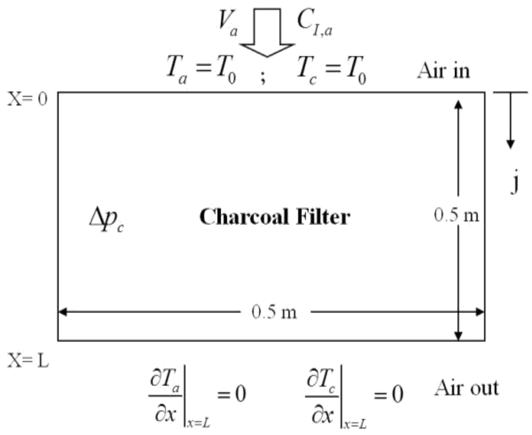


FIG 1: CHARCOAL FILTER CONCEPTUAL MODEL

2.1 Governing Equations 2.1.1 Charcoal bed

The energy balance over the charcoal includes diffusion, convection, the decay heat produced Q_d by retained radioactive material and the heat taken by

$$M_c C_{pc}\left(\frac{\partial T_c}{\partial t}\right)=\left[\left(K_c A_c L\right)\left(\frac{\partial^2 T_c}{\partial x^2}\right)+Q_d-Q_a\right] \qquad (1)$$

Where, ${}_{a}Q$ can be expressed in two ways [2], one is based on the temperature raise in air and the second is based on the overall heat transfer coefficient between the charcoal and the incoming air, given in Eq-2, 3.

$$Q_a=\rho_a.A_c.V_a.C_{pa}.\left(T_{a,out}-T_{a,in}\right) \qquad (2)$$

$$Q_a=h.A_c.L.\left(T_c-T_a\right) \qquad (3)$$

The Heat Transfer Coefficient (h) in charcoal filter w.r.t air velocity and filter porosity given in Eq-4[3]. Mathematical expression for ${}_{d}Q$ is given in Eq-5.

$$h=0.022.\left(100.V_a.\theta\right)^{0.66} \qquad (4)$$

$$Q_d=\left[\left[C_{I,a}.A_c.V_a\right].\left[(\text{Heat per Decay}).\left(\frac{6.023.10^{23}}{131}\right).e^{-[\lambda.t]}\right]\right] \qquad (5)$$

In the filtration process, the mass deposited in filter varies with the depth of the filter. An exponential expression is assumed for the mass deposition as a function of time and filter length, given in Eq-6 [1]

$$C_{I,x}=C_{I,x=0}.e^{-[\mathrm{B}x]} \qquad (6)$$

The value of B is estimated at each time such that the deposited mass is distributed exponentially within the charcoal bed (Eq-7).

$$C_{I,a}.A_c.V_a.\Delta t=\int_{x=0}^{x=L} C_{I,x}\,dx \qquad (7)$$

The simplified form of Eq-7 for calculating the value of is given in Eq-8. Eq-8 is a non-linear equation and is solved to get the value of constant B.

$$\left[\frac{C_{I,a}.A_c.V_a.\Delta t}{C_{I,x=0}}\right]=\left[\frac{1-e^{-[\mathrm{B}.L]}}{\mathrm{B}}\right] \qquad (8)$$

2.1.2 Air

The energy balance for the air flowing through the charcoal filter is given in Eq-9[4]. The coupling between the charcoal bed and air energy balances is included in the calculation of ${}_{a}Q$ term.

$$\rho_a C_{pa}\left(\frac{\partial T_a}{\partial t}\right)=Q_a-V_a\rho_a C_{pa}\left(\frac{\partial T_a}{\partial x}\right) \qquad (9)$$

3. NUMERICAL MODEL

The descritization of the mathematical expressions were performed based on Crank-Nicolson finite difference approximation. In the descritization equation the suffix j-represents the position (Along the filter length) and n– represent the filtration time. The discretized linear equations were solved with a Tridiagonal matrix algorithm and the algorithm was developed in FORTRAN.

3.1 Charcoal bed

The charcoal energy balance (Eq-1) is discretized based on Crank-Nicolson finite difference approximation as follows.

$$M_c.C_{pc}.\left[\frac{T^{n+1}_{c,j}-T^{n}_{c,j}}{\Delta t}\right]=\left[\frac{(K_c.A_c.\Delta x)}{2}\left(\frac{T^{n+1}_{c,j+1}-2.T^{n+1}_{c,j}+T^{n+1}_{c,j-1}}{\Delta x^2}+\frac{T^{n}_{c,j+1}-2.T^{n}_{c,j}+T^{n}_{c,j-1}}{\Delta x^2}\right)\right]$$

$$-\left[0.022(100.V_a.\theta)^{0.66}.A_c.\Delta x\left(\frac{T^{n+1}_{c,j}+T^{n}_{c,j}}{2}-T^{n}_{a,j}\right)\right]$$

$$+\left[\frac{C_{I,x=0}}{B}\left(e^{-[\mathrm{B}.\Delta \mathrm{x}]}-e^{-[\mathrm{B}.(x+\Delta \mathrm{x})]}\right).\left(\frac{6.023.10^{23}}{131}\right).(\text{Heat per Decay}).e^{-[\lambda.\Delta t]}\right]$$

3.2 Air

The flowing air energy balance (Eq-9) is discretized based on Crank-Nicolson finite difference approximation as follows.

$$\left[0.022(100.V_a.\theta)^{0.66}.A_c.\Delta x\left(T^{n+1}_{c,j}-\frac{T^{n+1}_{a,j}+T^{n}_{a,j}}{2}\right).(0.9)\right]=\rho_a C_{pa}\left[\frac{T^{n+1}_{a,j}-T^{n}_{a,j}}{\Delta t}\right]$$

$$-\frac{V_a\rho_a C_{pa}}{2}\left(\frac{T^{n+1}_{a,j+1}-T^{n+1}_{a,j-1}}{2\Delta x}+\frac{T^{n}_{a,j+1}-T^{n}_{a,j-1}}{2\Delta x}\right)$$

The deposition of iodine in charcoal is calculated based on assumed exponential deposition pattern (Eq-7). The method of calculations is as follows; initially total deposited mass of radioactive material is calculated in a given time step (). Then, the exponential expression (Eq-6) with an unknown exponent is integrated over the length of the charcoal bed and equated to the actual deposited mass to get the unknown exponent value. The same procedure is followed for every time step, which includes the addition of the entire previous time step mass and excludes the decay mass of the radioactive material. The maximum deposited mass at the filter entrance is considered based on reported data [5]. The calculated exponent (B) is used to get the mass deposition in filter in the direction of air flow.

3.3 Boundary conditions

Initial conditions: $T^0_{c,j}=298 \text{ for all } j \;;\; T^0_{a,j}=298 \text{ for all } j$

Boundary conditions:

$$T^n_{c,1}=T^0_{c,j} \text{ for all } n \quad ; \quad T^n_{a,1}=T^0_{a,j} \text{ for all } n$$

$$\left(\frac{dT^n_{c,j}}{dx}\right)_{x=L}=0 \text{ for all } n \quad ; \quad \left(\frac{dT^n_{a,j}}{dx}\right)_{x=L}=0 \text{ for all } n$$

3.4 Input parameters

The required parameters for the model are taken from the literature [5, 6and 7] and given in Table-1.

TABLE 1: INPUT PARAMETERS

Parameter	Value
ρ_c = Charcoal density (kg/m^3)	980
ρ_a = Density of incoming air (kg/m^3)	1.193
C_{pc} = Charcoal specific heat (J/kg.K)	840
C_{pa} = Air specific heat (J/kg.K)	1005
K_c =Charcoal thermal conductivity (W/m.K)	0.084
T_a = Air temperature (K)	298
A_c = Filter cross-section area (m^2)	0.25
x = Filter thickness (m)	0.5
V_a = Air velocity (m/s)	1
θ = Filter porosity	0.3
λ = Iodine decay constant (day^{-1})	8.05 days

4. RESULTS AND DISCUSSIONS

The above model was used for simulating the temperature transients in charcoal filter at different air flow rates, iodine concentrations and time dependent iodine concentrations. The obtained results are discussed in the following sections.

4.1 Temperature variation in charcoal & air

Temperature transients in charcoal filter are predicted for a filtration period of 3hrs and plotted in Fig 2. It shows the variations of charcoal temperature with time along the length of the charcoal filter. It can be seen from Fig 2 that temperature is not uniform across the filter thickness. Also the charcoal temperature increases with the time of filtration. Maximum temperature is observed within a small depth from the filter entrance. A small temperature rise of 29 K is observed at the exit of the filter even the maximum temperature raise is 60 K.

entrance and is decreases with filter depth. As in Fig 4, uniform temperatures between charcoal and air are attained at different depths w.r.t filtration time.

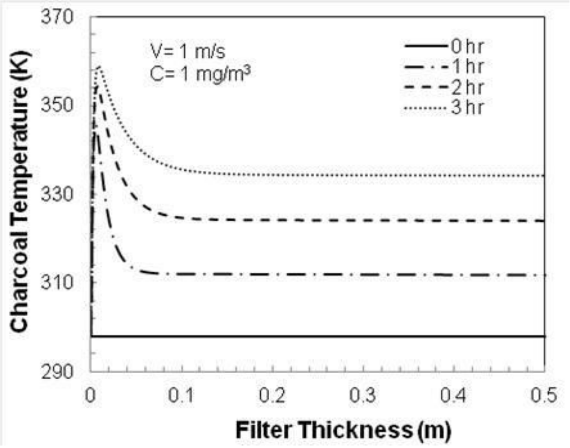


FIG 2: CHARCOAL TEMPERATURE VARIATION

The flowing air temperatures also simulated and plotted in Fig 3. It shows almost the constant temperature along the length except near to the entrance. As in Fig 3, the maximum air temperature raise is 29 K which is equal to the charcoal temperature at the exit. For comparison, both Charcoal and air temperatures were plotted together in Fig 4. It can be observed from Fig 4 that difference between the charcoal and air temperatures is higher near to filter entrance and is decreases with filter depth. As in Fig 4, uniform temperatures between charcoal and air are attained at different depths w.r.t filtration time.

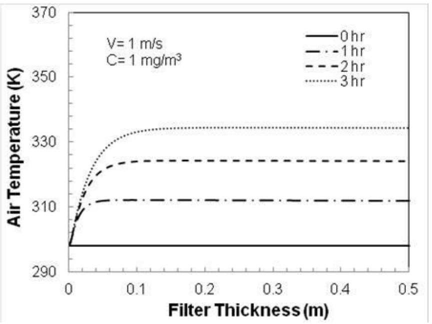


FIG 3: FLOWING AIR TEMPERATURE VARIATION HRS

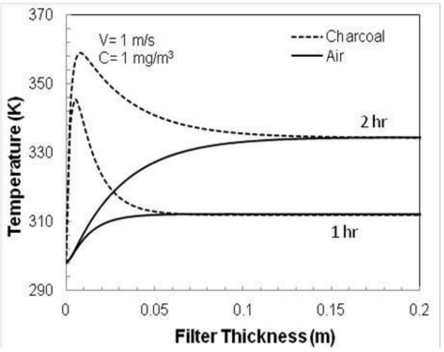


FIG 4: CHARCOAL & AIR TEMPERATURES AT 1& 2

It can be observed in Fig 2 that there is a non-linear variation in temperature along the filter length. However, charcoal has an ignition point of around 473 K; so maximum temperature in charcoal is an important parameter to assess the filter performance. Maximum & average temperatures are plotted in Fig 5. From Fig 5, the maximum temperature is 60 K and the average temperature is 30 K. The difference between maximum & average temperatures is increases and then gradually decreases.

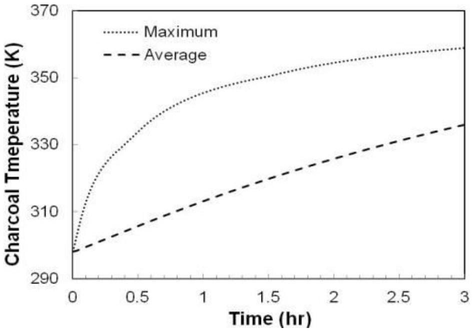


FIG 5: MAX & AVERAGE TEMPERATURES

Charcoal temperatures at entrance, exit of the filter and the maximum temperature are plotted in Fig 6. At the filter exit air temperature approaches the charcoal bed temperature. With time, charcoal temperature at entrance & exit were tending to reach same temperature. Fig 6 shows that the maximum temperature location is neither entrance nor at the filter exit.

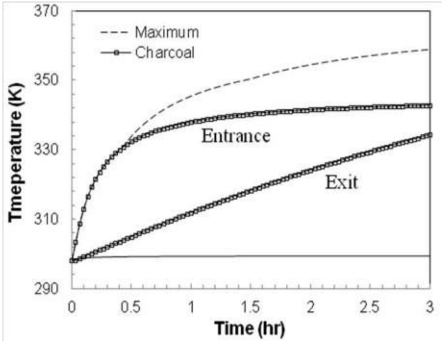
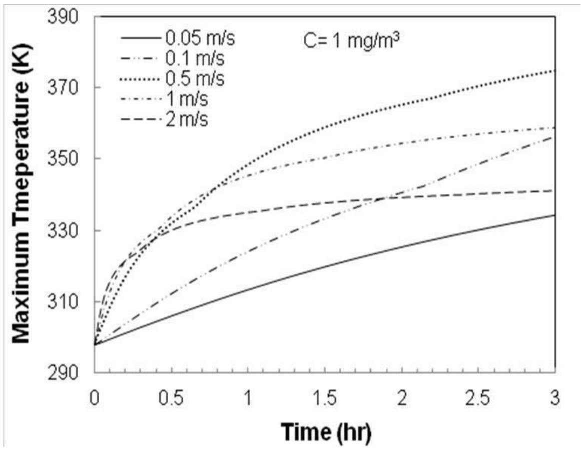


FIG 6: TEMPERATURES AT FILTER ENTRY &EXIT

4.2 Iodine deposition

The amount of iodine deposited is one of the key parameters affecting the temperature transients in filter. The deposition of iodine along filter length is plotted in Fig 7. The thickness of iodine deposition zone is increases with filtration time. This deposition pattern is kept on moving into the charcoal bed with time. This deposition pattern may vary with iodine deposition and the iodine decay. From Fig 7, it is clear that the considered charcoal filter of 0.5m thickness can provide a removal efficiency of 99.9%.

FIG 7: IODINE DEPOSITION IN CHARCOAL



4.3 Parametric study

Subsequent to the above studies, parametric studies are conducted w.r.t air flow and iodine concentration, discussed as follows.

4.3.1 Influence of air flow rate

The influence of air flow on charcoal bed temperatures is obtained with different air flow rates keeping other parameters constant. The maximum charcoal bed temperatures at different air flow rates shown in Fig 8. Here, air flow rate shows positive as well as negative influence on temperature rise. From Fig 8, it can be observed that at lower flow range i.e. (below 0.5 m/s); the temperature gradually increases. This may be because of at lower flow rate the decay heat dominating more than that of air convection term. At higher flow rate, the rate of deposition is more thereby increases the temperature and at FIG 9: EFFECT OF CONVECTION

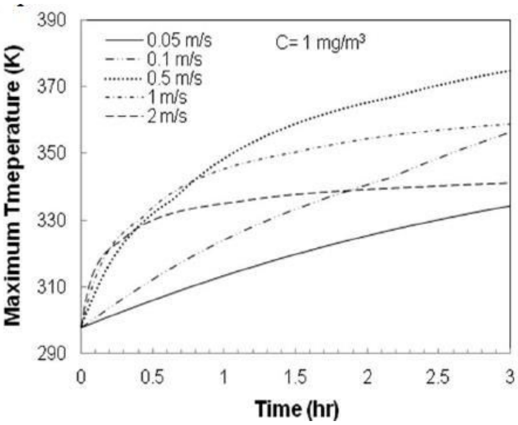


FIG 8: INFLUENCE OF AIR FLOW RATE (M/S)

The effect of air convection on charcoal temperature can be seen in Fig 9, this plot shows the charcoal temperature at different flow rate after 1.5 hr of filtration time. Here, at 1 m/s the maximum temperature is more than that at higher flow rate 2m/s. Whereas at 2 m/s, the maximum temperature is less but the temperature in the remaining part of the filter is more. This may be because of strong air convective transfer.

4.3.2 Influence of Iodine concentration

At fixed air flow rate (1 m/s) and filter properties, simulations were performed for different iodine concentration in incoming air, shown in Fig 10.

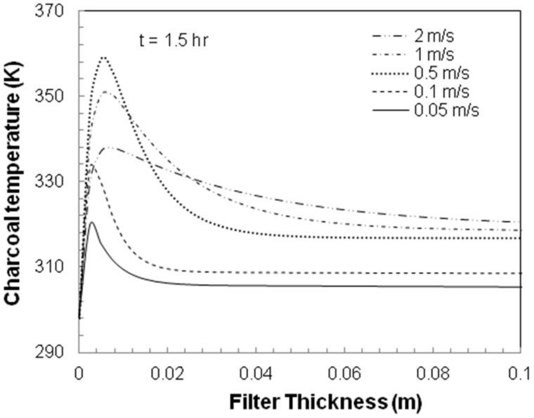


FIG 9: EFFECT OF CONVECTION

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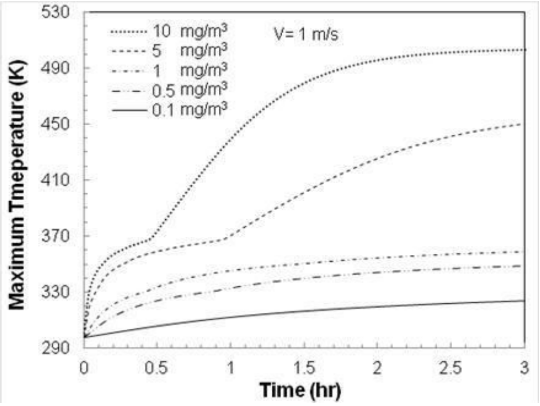

FIG 10: INFLUENCE OF IODINE CONCENTRATION

From Fig 10, it can be seen that the maximum charcoal bed temperature increases with iodine concentration. At lower concentrations temperature raise is gradual, at higher concentrations temperature raise is rapid. This may be because of the role played by the convective heat transfer and decay heats. For 10 mg/m^3 iodine concentration; decay heat dominates convective heat transfer in stage wise manner. However, at higher iodine concentrations charcoal temperature may exceed the charcoal ignition point.

4.4 Time dependent Iodine input

Under accidental conditions, iodine concentration in reactor containments varies with time depending upon the releasing rates. A case has been considered for charcoal temperature evaluation for time dependent iodine concentration in incoming air. In this a variable iodine concentration input was given with exponential variation. A maximum initial concentration of 10 mg/m^3 is taken and is decreasing exponentially to zero in 3 hrs (Fig 11).

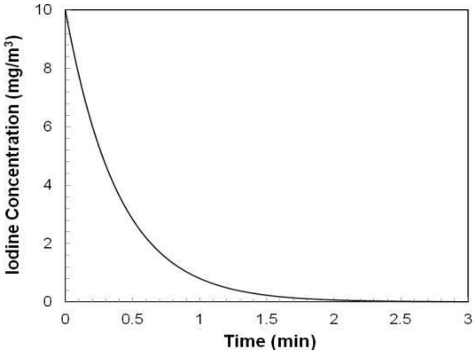

FIG 11: TIME DEPENDENT IODINE IN AIR

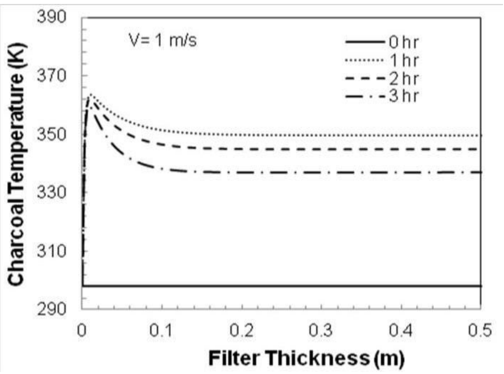

FIG 12: TEMPERATURES FOR TIME DEPENDENT IODINE

Simulations were performed for the charcoal and air temperatures with the specified exponential iodine concnetaions by keeping other parameters constant. The simulated results were plotted in Fig 12 , which shows the charocoal temperature along filter with time. It can be observed that, temperature in the charcoal increases and then decreases gradually. The temeperature trend is similar to the trend that of at constant iodine concentration. The temperature varition at enterace, exit and maximum temperature are plotted in Fig 13. As in Fig 13, The charcoal bed temperature at the entrace increases rapidly than at exit. Charcoal bed temperature at exit decreases quickly than that of entrance tempearutre; this is due to heat produced by deposited iodine at the filter entrace.

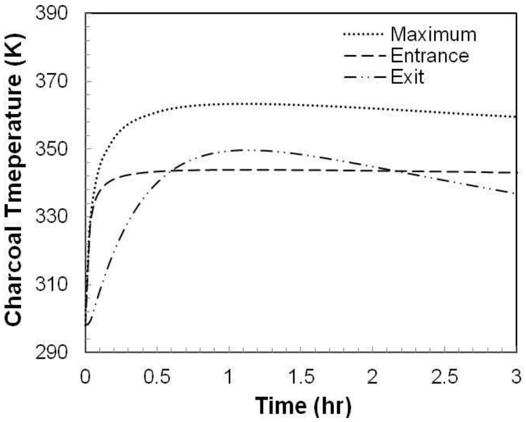

FIG 13: TEMPERATURE AT FILTER ENTRY & EXIT

5. CONCLUSIONS

- Charcoal bed temperature raise is not uniform along the filter and maximum temperature is observed near to filter entrance.
- At 1mg/m^3 of iodine, higher charcoal temperature is observed at 0.5 m/s and at all other flow rates less/more than 0.5 m/s charcoal bed is at lower temperature.
- The Max temperature trend is different with iodine concentration. Charcoal temperature may exceed its ignition point at higher iodine concentrations and at lower flow rate.
- For exponential decay iodine input, charcoal temperature increases rapidly and decreases gradually with time.

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