POLLUTANTS EMISSION AND DISPERSION FROM ELEVATED GAS FLARE: C.S. OF AGHAJARY

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ABSTRACT

The purpose of this research is to study the emission and dispersion of hydrogen sulfide gas (H₂S) from elevated flare in Aghajary compression station. This flare is used only during shut-down or start-up. This flare has ignition system, when the feed gas discharged to the flare will be ignited by sparks. It is very likely that the ignition system does not work or ignition is delayed. In this situation H₂S may come down to the ground level and if it's concentration be greater than 8 ppm it can endanger human health and lead to death. Gaussian-based dispersion models are widely used to estimate local pollution levels. The accuracy of such models depends on stability classification schemes as well as plume rise equations. A general plume dispersion model for a point source emission, based on Gaussian plume dispersion equation, was developed. A mathematical model formulated in a computer program written in Pascal language was utilized in finding the ground level concentrations of H₂S emitted from the elevated flare and final results compare with PHAST software results.

INTRODUCTION

Air pollution is dangerous problem facing humans, and it caused great harmful which may cause death especially when it is higher than the critical environmental limits of pollutants. Oil and gas activities is one of the most important pollution source and very toxic gas emitted in environment in this industry. A large number of oil reservoirs have hydrogen sulfide gas in their components. H₂S during the oil processing is separated from oil, if there are processing facilities sent to refinery otherwise discharge to flare for burning, as well as in shut down and start up usually gas sent to flare. The flares system is safety equipment necessary in petroleum plants. Flares are designed to avoid the uncontrolled emissions. It is used for two cases related strongly with safety, one of them is during the unstable operations such as start-up, shut down of unit operations; the second case is to management the waste gases discharged from routine production operations. Elevated flare is a one type of flares, it is a vertical pipe opened from its top sup-

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plied with igniters.

The waste or discharged gases are burned with atmospheric air at the tip of flare stack. Aghajary compression station is located in south of Iran, its flare is elevated type with ignition system and during uncontrolled process or in shut down and start-up is used. In this investigation dispersion of H₂S emitted from this flare at ignition failure has been study. Gaussian model written in Pascal language and PHAST software is used for gas dispersion study. The programmed model and software model takes into consideration the meteorological conditions (wind speed, ambient temperature, and atmospheric stability) which may take place at the study region. According to OSHA standard the maximum H₂S allowable ground level concentration (MGLC) for 8 hours working is 8 ppm and for 10 minutes is 20-50 ppm and 100 ppm dangerous for life Health immediately. Table 1 shows the feed gas composition and specifications of flare and ambient condition are shown in Table 2.

One of the research at this case belong to Hatam Asal Gzar and Khamaal Muhsin Kseer (2009) in this research they studied pollution emission and dispersion from several flare in Iraq by using Gaussian model. Seema Awasthi, Mukesh Khare and Prashant Gargav (2006) studied the pollution dispersion of power plant flare by using Gaussian model.

**Theoretical Basis of dispersion air pollutants emitted from flares**

Mathematical model formulating in a computer program written in Pascal language using Gaussian equation is utilized to investigate the dispersion process and distribution of pollutants (H₂S) emitted from the elevated flare. With Gaussian equation (1) the ground level concentrations of H₂S is determined.

\[
C = \frac{Q}{2\pi u y z} \exp \left[-\frac{y^2}{2\sigma_y^2} \right] \exp \left[-\frac{(H - z)^2}{2\sigma_z^2} \right] + \exp \left[-\frac{(H + z)^2}{2\sigma_z^2} \right]
\]

(1)

Where,

C : Air pollutant concentration in mass per volume (g/m³)
Q : Pollutant emission rate in mass per time (g/s)
u : Wind speed at point of release (m/s)
y : Crosswind direction standard deviation of the concentration distribution at downwind distance x
z : Vertical direction standard deviation of the concentration distribution at downwind distance

The Maximum Ground Level Concentration (MGLC) is usually of interest. It will occur at some downwind distance right below the centerline of the plume (y = 0, z = 0) then Eq. (1) is reduced to:

\[
\left(\frac{C}{Q}\right)_{ground} = \frac{1}{\pi\sigma_y\sigma_z} \exp \left[-\frac{(H)^2}{2\sigma_z^2} \right]
\]

(2)

**Correlation for MGLC**

Using Eq. (2) to calculate MGLC requires one to generate repetitious solution. In order to approximate MGLC, without calculating Eq. (2), many times a correlation formula has been generated by using the MGLC graph presented in the Workbook is been used. The values of the constants are listed in Table 3.

\[
\left(\frac{C}{Q}\right)_{\text{max}} = \exp\left[at + b(H) + c(H)^2 + d(H)^3\right]
\]

(3)

Where,

(C/Q)_{\text{max}} : maximum ground level concentration
(a, b, c, d) : Coefficients for a given stability condition

**Table 1.** Feed gas composition and specifications of flare

<table>
<thead>
<tr>
<th>Composition/spec.</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.8327</td>
</tr>
<tr>
<td>C2</td>
<td>0.0692</td>
</tr>
<tr>
<td>C3</td>
<td>0.0316</td>
</tr>
<tr>
<td>C4</td>
<td>0.104</td>
</tr>
<tr>
<td>N2</td>
<td>0.0210</td>
</tr>
<tr>
<td>CO2</td>
<td>0.0263</td>
</tr>
<tr>
<td>H2S</td>
<td>0.0088</td>
</tr>
<tr>
<td>T(C)</td>
<td>38</td>
</tr>
<tr>
<td>MW</td>
<td>19.67</td>
</tr>
<tr>
<td>Height of flare(m)</td>
<td>70</td>
</tr>
<tr>
<td>Diameter(mm)</td>
<td>1067</td>
</tr>
<tr>
<td>FLOW RATE(MMSCFD)</td>
<td>620</td>
</tr>
</tbody>
</table>

**Table 2.** Ambient condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ambient temperature (°C)</td>
<td>24.5</td>
</tr>
<tr>
<td>Average ambient wind velocity (m/s)</td>
<td>4</td>
</tr>
<tr>
<td>Average ambient humidity(%)</td>
<td>46</td>
</tr>
</tbody>
</table>
H: Effective height of the centerline of the pollutant plume (m)
Calculating the distance correspond to MGLC, \( x_{\text{max}} \) is also important. Eq. (4) for \( x_{\text{max}} \) are developed using the same regression and format of equation as Ranchoux's book.

\[
x_{\text{max}} = \exp \left[ a + b (\ln H) + c (\ln H)^2 + d (\ln H)^3 \right]
\]

(4)

<table>
<thead>
<tr>
<th>Stability Class</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-1.0563</td>
<td>-2.7153</td>
<td>0.1261</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>-1.8060</td>
<td>-2.1912</td>
<td>0.0389</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>-1.9748</td>
<td>-1.9980</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>-2.5302</td>
<td>-1.5610</td>
<td>-0.0934</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>-1.4496</td>
<td>-2.5910</td>
<td>0.2181</td>
<td>-0.0343</td>
</tr>
<tr>
<td>F</td>
<td>-1.0488</td>
<td>-3.2252</td>
<td>0.4977</td>
<td>-0.0765</td>
</tr>
</tbody>
</table>

5. Visualization of results.
In this study a Multiple Cell Model was used for pollution dispersion from an industrial stack emissions. Figure (1) shows the mass balance for an unknown cell.

\[
\frac{\partial C}{\partial t} + \frac{\partial (u C)}{\partial x} + \frac{\partial (v C)}{\partial y} + \frac{\partial (w C)}{\partial z} = \frac{\partial}{\partial x} \left( \frac{\partial C}{\partial x} + \frac{K}{\rho} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial y} \left( \frac{K}{\rho} \frac{\partial C}{\partial y} + \frac{\partial (K_{s1} C)}{\partial z} \right) + e_{s1} + K_{s2} C + Q_{s}(c_{1}, c_{2}, \ldots, c_{q}), \quad s=1,2,\ldots,q
\]

(5)

Five major physical and chemical processes are to be considered when an air pollution model is developed. These processes are: (i) horizontal transport (advection), (ii) horizontal diffusion, (iii) deposition (both dry deposition and wet deposition), (iv) chemical reactions plus emissions and (v) vertical transport and diffusion. The mathematical description of these processes leads to a system of partial differential equation:

Where,
C: the concentration of the chemical species involved in the model
\( u, v \) and \( w \): wind velocities
\( K_{x}, K_{y} \) and \( K_{z} \): diffusion coefficients
\( E_{s} \): the emission sources
\( K_{s} \): and \( K_{s1} \): deposition coefficients (for the dry deposition and the wet deposition, respectively)
\( Q_{s}(c_{1}, c_{2}, \ldots, c_{q}) \): chemical reactions.

6. Assumptions
For this kind of systems, the following assumptions are employed:
1. Steady state condition
2. \( v=w=0 \)
3. Transport by bulk motion in the x-direction exceeds diffusion in the x-direction (K1s=K2s=0)
4. There is no deposition in system (K1s=K2s=0)
5. There is no reaction in system (Qs=0)

By applying the above assumptions, Eq. (5) reduces to:

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\partial C}{\partial x} + \frac{K}{\rho} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial y} \left( \frac{K}{\rho} \frac{\partial C}{\partial y} + \frac{\partial (K_{s1} C)}{\partial z} \right) + e_{s1} + K_{s2} C + Q_{s}(c_{1}, c_{2}, \ldots, c_{q})
\]

(6)

Initial and Boundary Conditions
For solving Eq. (6), the following initial and boundary conditions are used:
at \( x = 0 \), \( C(0,j,k) = 0 \)

at \( y = 0 \), \( \frac{\partial C}{\partial y} = 0 \)

at \( y = W \), \( \frac{\partial C}{\partial y} = 0 \)

at \( z = 0 \), \( \frac{\partial C}{\partial z} = 0 \)

at \( z = \) mixing length, \( \frac{\partial C}{\partial z} = 0 \)

\[
\begin{align*}
\frac{\partial C}{\partial x}_{i,j,k} &= \frac{1}{2\Delta x}(C_{i+1,j,k} + C_{i-1,j,k} - 2C_{i,j,k}) \quad (7) \\
\frac{\partial^2 C}{\partial y^2}_{i,j,k} &= \frac{1}{\Delta y^2}(C_{i,j+1,k} + C_{i,j-1,k} - 2C_{i,j,k}) \quad (8) \\
\frac{\partial^2 C}{\partial z^2}_{i,j,k} &= \frac{1}{\Delta z^2}(C_{i,j,k+1} + C_{i,j,k-1} - 2C_{i,j,k}) \quad (9)
\end{align*}
\]

\[
Q = g\Delta y\Delta z \\
R = rC^m
\]

By substitution in equation (2), we have:

\[
U_y \frac{\partial C}{\partial y} = \frac{1}{\Delta y} \left[ \frac{\partial}{\partial y} \left( \frac{\partial C}{\partial y} \right) \Delta z + (K_y) \frac{\partial C}{\partial y} \Delta y \Delta z \right] \\
+ (K_y) \frac{\partial^2 C}{\partial y^2} \Delta y \Delta z \\
+ (K_y) \frac{\partial^2 C}{\partial y^2} \Delta z \\
+ (K_y) \frac{\partial^2 C}{\partial y^2} \Delta z \\
+ \frac{\partial C}{\partial y} \Delta y \Delta z \\
+ \frac{\partial C}{\partial z} \Delta z \\
+ \frac{\partial C}{\partial z} \Delta z
\]

(12)

Where, values of wind speed and eddy diffusivity are presumed known. This is an explicit algebraic formula and may be unstable in some conditions. The stability condition for this system is:

\[
\Delta y \leq \frac{U_y}{2K_y \left( \frac{5}{\Delta y^2} + \frac{1}{\Delta z^2} \right)}
\]

(13)

**Atmospheric Parameters**

Atmospheric conditions are a driving force in the formation, dispersion and transport of pollutant plumes. For solving Eq. (12) we need atmospheric parameters like, wind speed, plume rise, stability category, dispersion coefficients, surface roughness and other parameters. Required equations and values for determining that parameters are as:

**Atmospheric Stability**

Stability of the atmosphere varies hourly, but for modeling purposes, for short time periods (1-3 hr) a constant and representative atmospheric stability was assumed. In this research three classes of atmosphere stability, neutral, stable and unstable are considered. Atmospheric stability is calculated by using the following equation:

\[
L = \frac{u' \cdot 3 \cdot C_p \rho T}{kgH_n}
\]

(14)

In equation (14), \( u' \) is friction velocity, \( C_p \) is specific heat of air, \( T \) is air temperature, \( k \) is Karman’s constant
\( (k=0.4) \), \( g \) is gravitational constant and \( H_n \) is net heat that enters the atmosphere. \( H_n \) for neutral atmosphere is 0, for stable atmosphere is -42 and for unstable atmosphere is 175. We see that \( L \) is simply the height above the ground at which the production of turbulence by both mechanical and boundary forces is equal.

**Surface Roughness and Friction Velocity**

It is convenient to introduce a drag coefficient, \( c'_{\theta} \), based on the geostrophic wind, \( U_g \), such that

\[
U_* = c'_{\theta} U_g \tag{15}
\]

The geostrophic drag coefficient is a function of the surface Rossby Number

\( (R_o = u g / f Z_0) \) and \( L \), where \( f \) is the Coriolis parameter of the earth and \( Z_0 \) is surface roughness. Lettau suggests the following empirical relationship for a neutral atmosphere:

\[
c'_{\theta} = 0.16 \left[ \log_{10}(R_o) - 1.8 \right] \tag{16}
\]

For stable and unstable atmosphere it must be multiplied by 0.6 and 1.2, respectively. Values of Roughness length \( (Z_o) \) and friction velocity \( (u^*) \) for several different land surfaces are presented in Heinsohn. Table 4 defines values of Roughness length \( (Z_o) \) and friction velocity \( (u^*) \) for several different land surfaces.

**Table 4. Roughness lengths and friction velocity**

<table>
<thead>
<tr>
<th>Surface</th>
<th>( Z_o ) (CM)</th>
<th>( u^* ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very smooth (ice, mud flats)</td>
<td>0.001</td>
<td>0.16</td>
</tr>
<tr>
<td>Snow</td>
<td>0.0001-0.005</td>
<td>0.17</td>
</tr>
<tr>
<td>Smooth sea</td>
<td>0.0001-0.02</td>
<td>0.21</td>
</tr>
<tr>
<td>Level desert</td>
<td>0.0001-0.03</td>
<td>0.22</td>
</tr>
<tr>
<td>Lawn, grass up to 1 cm high</td>
<td>0.1</td>
<td>0.27</td>
</tr>
<tr>
<td>Lawn, grass up to 5 cm high</td>
<td>1-2</td>
<td>0.43</td>
</tr>
<tr>
<td>Lawn, grass up to 50 cm high</td>
<td>4-9</td>
<td>0.60</td>
</tr>
<tr>
<td>Fully grown root crops</td>
<td>10-14</td>
<td>1.75</td>
</tr>
<tr>
<td>Tree covered</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Low-density residential</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>Central business district</td>
<td>500-10000</td>
<td>-</td>
</tr>
</tbody>
</table>

**Plume Rise**

When the air contaminants are emitted from a stack, they rise above the stack before drifting a significant distance downwind. The effective stack height \( H \) is not only the physical stack's height \( h_s \) but include also the plume rise (Fig. 3).

\[
H = h_s + \delta h \tag{17}
\]

The stack height used in the calculations must be the effective stack height. Usually, Briggs' equation and Holland's equation are used for prediction of plume rise. Briggs' and Holland's equations are given by equations (34) and (35) respectively.

\[
\delta h = \frac{H_{0.8}^2}{H} \tag{18}
\]

\[
\delta h = \frac{\nu D}{u} \left( 1.5 + 2.68 \times 10^{-3} PD \frac{T_s - T_a}{T_s} \right) \tag{19}
\]

Where,

\( \nu \) : stack exit velocity (m/s)
\( D \) : stack diameter (m)
\( u \) : wind velocity (m/s) measured or calculated at the height, \( h_s \)
\( P \) : pressure (mbar)
\( T_s \) : stack gas temperature (K)
\( T_a \) : atmosphere temperature (K)

**Wind Velocity and Dispersion Coefficients**

The wind power law is used to adjust the observed wind speed, \( u_{ref} \), from a reference measurement height, \( z_{ref} \), to the stack or release height, \( h_s \). The power law equation is of the form:
Where \( p \) is the wind profile exponent. Values of \( p \) may be provided by the user as a function of stability category and wind speed class.

RESULTS AND DISCUSSION

Comparison between computer program model and PHAST model is with neutral stability condition is presented in figure 5 and 6. There is good match between the two models and maximum deviation is about 11%. As is clear from these graphs after short distance from flare concentration become 1/3 and after that With a lower slope decreases As well as with increasing wind velocity mixing length decreases too.

Fig. 4 \( H_2S \) centerline concentration with \( u=4 \) m/s

Fig. 5 \( H_2S \) centerline concentration with \( u=8 \) m/s

As previously mentioned, it is very important we find MGLC for this purpose 32 different cases defined. Each case has special meteorological conditions with 45 and 70(m) flare height. We look for with which condition MGLC is greater than 8 ppm until necessary instruction to be considered. For reach our goal three stability condition, very unstable, neutral and very stable with various wind velocity are considered. All of these condition occur during the year. Tables 5 and 6 are shown MGLC and it’s distance(\( x_{\text{max}} \)) for two flares.

As results at neutral condition for two flare MGLC is zero and in this condition operators have enough time to stop the operation and for other weather condition, A(very unstable) and G(very stable) MGLC not zero but concentration flare with 70 m height not greater than 8 ppm thus operator do not do any thing but it is better to end the operation for the first time. The height of Aghajary flare is 70 m and another flare with 45 m height consider for second alternative, if it is possible the height of flare reduced however, for second flare MGLC equal 8 and in situation 8 hours existing for reaction.

Other important result is, increasing wind velocity in very unstable(A) condition decrease the \( x_{\text{max}} \) and MGLC but in very stable(G) condition wind velocity increasing, decrease MGLC and increase \( x_{\text{max}} \).

Table 5. Maximum ground level concentration for Aghajary flare

<table>
<thead>
<tr>
<th>Case</th>
<th>Flare height</th>
<th>Weather category</th>
<th>Wind velocity</th>
<th>MGLC</th>
<th>( x_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>70</td>
<td>A</td>
<td>4</td>
<td>5</td>
<td>345</td>
</tr>
<tr>
<td>02</td>
<td>70</td>
<td>A</td>
<td>8</td>
<td>3</td>
<td>308</td>
</tr>
<tr>
<td>03</td>
<td>70</td>
<td>A</td>
<td>10</td>
<td>3</td>
<td>268</td>
</tr>
<tr>
<td>04</td>
<td>70</td>
<td>A</td>
<td>20</td>
<td>5</td>
<td>284</td>
</tr>
<tr>
<td>05</td>
<td>70</td>
<td>D</td>
<td>4</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>06</td>
<td>70</td>
<td>D</td>
<td>8</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>07</td>
<td>70</td>
<td>D</td>
<td>10</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>08</td>
<td>70</td>
<td>D</td>
<td>20</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>09</td>
<td>70</td>
<td>G</td>
<td>4</td>
<td>7</td>
<td>640</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>G</td>
<td>8</td>
<td>3</td>
<td>10500</td>
</tr>
<tr>
<td>11</td>
<td>70</td>
<td>G</td>
<td>10</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>12</td>
<td>70</td>
<td>G</td>
<td>20</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 6. Maximum ground level concentration for flare with 45 m height

<table>
<thead>
<tr>
<th>Case</th>
<th>Flare height</th>
<th>Weather category</th>
<th>Wind velocity</th>
<th>MGLC</th>
<th>( x_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>45</td>
<td>A</td>
<td>4</td>
<td>5</td>
<td>335</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>A</td>
<td>8</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>A</td>
<td>8</td>
<td>10</td>
<td>160</td>
</tr>
<tr>
<td>16</td>
<td>45</td>
<td>A</td>
<td>8</td>
<td>20</td>
<td>105</td>
</tr>
<tr>
<td>17</td>
<td>45</td>
<td>D</td>
<td>0</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>18</td>
<td>45</td>
<td>D</td>
<td>0</td>
<td>8</td>
<td>—</td>
</tr>
<tr>
<td>19</td>
<td>45</td>
<td>D</td>
<td>0</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>20</td>
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<td>0</td>
<td>—</td>
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<td>21</td>
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<td>4</td>
<td>8</td>
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<tr>
<td>22</td>
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<td>1</td>
<td>8</td>
<td>2000</td>
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<td>23</td>
<td>45</td>
<td>G</td>
<td>1</td>
<td>10</td>
<td>5980</td>
</tr>
<tr>
<td>24</td>
<td>45</td>
<td>G</td>
<td>0</td>
<td>20</td>
<td>—</td>
</tr>
</tbody>
</table>

Contour of \( H_2S \) distributing at several cases are shown in following Figures.

Other results that can be achieved graphs about mixing length and downwind distance, at A,D and G weather conditions with increasing wind velocity mixing length is reduced but for cloud length at A condition reduction is seen and at D and G increasing. Generally, maximum cloud height in the neutral weather condition and minimum in the very stable condition, cloud height in the very stable condition is very greater than other conditions at a equal wind velocity an minimum was occurred at very unstable condition.

Because of the gas reached to the ground level at stability condition A and G, study other rang of wind velocity were important Therefore the problem was resolved for wind velocity less than 4 m/s and the
results are shown in Table 7.

As is clear from the results at stability condition A with decreasing wind velocity MGLC decreased and $x_{\text{max}}$ increased but the important results obtained at the G stability. In very stable condition with decreasing wind velocity MGLC increase quickly and very close to the flare ($x_{\text{max}} = 49$ m) MGLC be 100 ppm and this mean is death for each alive creature.

For further information some contour from critical cases are given below.

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