Study of Dynamic Sealing Characteristics in an Elevated Flare

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Abstract. Elevated flare is currently the most widely used flare systems in refineries and petrochemical, natural gas and coal gasification industries. Waste gases from upstream process must be burnt before releasing to the atmosphere. The emissions of combustible exhaust gases usually have large turndown ratios. The size of the flare is designed according to the maximum discharge condition. However, in the case of small flow rates, combustion can be highly unstable which affects the safety of the system. In practice, a dynamic seal is often installed on the flare header to prevent oxygen penetration. Inert gas is purged into the system to maintain a micro-positive pressure inside the flare header. Typically, the appropriate purge gas rate is decided on engineering experience which may not be able to ensure the operation safety. In this study, we carried out numerical simulations and experiments to investigate the fluid dynamics and oxygen concentration within a flare model. Typical working conditions are tested in experiment for validation purpose. The safe and economical purging speed is explored as well as the influencing factors to provide calculation methods and basis for the dynamic seal design.

1. Introduction
The elevated flare is currently the most widely used flare system in the petrochemical, natural gas and coal gasification industries. It is commonly recognized as the last safety barrier for all accidental events [1]. The combustible exhaust gas discharged from upstream processes which cannot be recycled or utilized has to be burnt by the flare before releasing to the environment. Flare size is usually designed according to the maximum discharge condition. When the flare is running under conditions of small discharge or no discharge, ambient air ingress often cause oxygen penetrating into the flare head, which might lead to an explosion accident. Therefore, it is necessary to provide a sealing device at the flare header, i.e. a molecular seal or a dynamic seal, and continuously inject purge gas to maintain a micro-positive pressure within the flare stack [2]. Compared with the molecular seal, the dynamic seal has a relatively simpler structure and wider application.

Purge gas consumption directly affects the safety and economy of the system. Typically, in domestic engineering design, the appropriate purge gas rate is decided based on experience [3]. This may not always ensure the safety of the device in real applications. There are many factors affecting the dynamic sealing purge speed. In this paper, we carry out numerical simulations based on incompressible computational fluid dynamics (CFD). Species contours are plotted to show the effect of the velocity seal. Important factors such as baffle size, baffle number, and baffle angle are analyzed. After the CFD results are obtained, some typical working conditions are tested in experiment for validation purpose. Our results show that the CFD results and the experimental data are in close agreement. Then the safe and economical purging speed and its important influencing factors are analyzed which provide basis for the design of the dynamic sealing device.
2. Dynamic seal
The dynamic seal is also called velocity seal. Figure 1 shows the structure and schematic of the seal. When the air ingestion happens, it flows downward along the stack wall until reaching the seal baffles [4]. Then the flow turns back. In the meanwhile, a certain amount of purge gas is continuously injected into the stack to further push the air out of the stack. Flow rate of the purging is typically small so that a micro-positive pressure is maintained. The scenario can be considered as a laminar flow which yields a parabolic velocity distribution. Thus the speed of the purge gas is the highest on the axis and lowest near the wall. When the purge gas flows through the baffle, it accelerates and flows out of the stack with the air entrained along the way.

![Figure 1 Dynamic seal in a flare header](image)

In this paper, nitrogen is used as the purge gas. The upper part of the gas (roughly the mixture of oxygen and nitrogen) has a slightly higher density than the nitrogen in the lower part. The upward movement of nitrogen has a small momentum, and the mixing between the air and the purging nitrogen happens in the baffle region. This is a complex density stratified flow problem (similar to thermal stratified flow), which has always been one of the important research topics and difficulties in the field of fluid mechanics, with complex unstable characteristics [5].

3. Numerical Simulations

3.1. Physical Model
A two dimensionally axisymmetric model and mesh is built using Gambit. Parametric study is carried out by varying the stack diameter (DN600, DN800, DN1000 and DN1600), the baffle angle (25°, 45° and 65°), the number of baffle layers (0, 1, and 3) and the throat area ratios (0.6, 0.7, and 0.8), i.e. 13 models in total.

Unstructured grid is applied throughout the mesh building process with finer mesh applied near the baffle region. The flare header is 5 m high. A cube with a height of 50 m and a width of 20 m is used as the ambient environment.

3.2. Mathematical model
In order to simplify the calculation and save the computation time, the following four assumptions are made,

- (1) the velocity of the flare header is a fully developed laminar flow;
- (2) the gas is a steady flow;
- (3) there is no temperature change;
- (4) The ambient wind speed is zero.
The CFD approach solves the Navier-Stokes equation through numerical discretization [6]. The dynamics of this mixing problem is governed by the non-reacting species transportation equation shown in Equation (1),

$$\frac{\partial}{\partial t} \left( \rho Y_i \right) + \nabla \cdot \left( \rho \mathbf{v} Y_i \right) = -\nabla \cdot \mathbf{J}_i \quad (1)$$

where $Y_i$ is the mass fraction of species $i$, and $\mathbf{J}_i$ is the diffusion flux of species $i$ which in a laminar flow can be written as,

$$\mathbf{J}_i = -\rho D_{i,a} \nabla Y_i \quad (2)$$

where $D_{i,a}$ is the mass diffusion coefficient for species $i$ [7].

In the above mathematical model, the partial differential equation is discretized using SIMPLEC algorithm, a semi-implicit method for solving pressure-coupled equations. The commercial CFD package ANSYS Fluent 13.0 is used for simulation.

### 3.3. Simulation results

Purging speed plays an important role in terms of reducing the oxygen concentration. Figure 2 shows the difference the purging speed can make to the oxygen level within the stack (purging speed is 0.020 m/s and 0.024 m/s respectively). Stack bottom is on the right with a velocity-inlet boundary condition. A purging rate of 0.020 m/s is not enough to resist the air ingress. The ambient air will gradually infiltrate below the baffle. As shown on the left in Figure 2, the oxygen concentration has reached about 6–8% which might cause a burn back. At a purge speed of 0.024 m/s, the oxygen concentration below the baffles stays below 3% which is safe [8].

![Figure 2 Contours of oxygen distribution](image)

### 3.3.1 Effect of stack diameter

For a baffle with a fixed angle, the oxygen level within the stack is affected by the stack diameter and the purging speed. Figure 3 shows the relationship between the oxygen concentration and the purging speed at a stack depth of 4m. The diameter of the stack varies from 600 mm to 1200 mm. The baffle angle is 45° and the throat area ratio is 0.8.

As shown in Figure 3, oxygen level drops very quickly with the purging speed. For a stack with a diameter of 1000 mm, when the purging flow rate increases from 0.008 m/s to 0.015 m/s, the internal oxygen concentration can be reduced by 38% and 43% respectively; when the purging flow rate continues to increase to 0.03 m/s, the oxygen concentration in the flare header can be reduced by 76%. The oxygen concentration is kept below 1.5%.
3.3.2 Effect of baffle structure
In this paper, three baffle angles of 25°, 45° and 65° are used under the same throat area for a stack size of 1000 mm. The simulation results are shown in Figure 4.

As shown in the figure, the larger the baffle angle, the longer the baffle length, and the more obvious the sealing effect. Under a purging speed of 0.03 m/s, oxygen level for the 65° case is less than 4%, almost half of the 25° case.
As shown in Figure 5, the baffle of the dynamic seal can certainly reduce the oxygen concentration. However, the baffle number doesn’t make too much difference. The oxygen concentration for the three-layer baffle case is almost the same with the single-layer baffle case.

![Figure 6 Oxygen concentration under different purging speed and throat area ratio](image)

Figure 6 Oxygen concentration under different purging speed and throat area ratio

At the baffle, the flow path becomes smaller, the ratio between the diameter of the baffle throat and the stack is called throat area ratio, which is noted as d:D. Figure 6 shows the oxygen concentration variation under different purging speed and throat area ratio. As shown in the figure, the smaller the throat area ratio, the less the purge flow rate is required. However, as the throat area ratio decreases, the resistance loss increases, which can cause big pressure drop within the flare header. Therefore there should be a reasonable ratio. In engineering practice, a ratio between 0.7 to 0.8 is used.

4. Experimental study

4.1. Test equipment and system

The test system mainly includes a liquid nitrogen cryogenic storage tank, a vaporizer, the pressure regulating devices, a flow meter and three oxygen concentration analysers. The dynamic seal is inside the flare stack.

![Figure 7 Experimental Setup](image)

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The test device has a flare height of 15 m and a diameter of 1 m. Three sets of oxygen concentration analysers were installed at 2.0 m, 4.0 m and 6.0 m below the stack outlet.
4.2. Results and analysis

4.2.1 Effect of baffle number
In this test model, conditions tested include cases with no baffle, a single-layer baffle and a three-layer baffle. The throat area ratio is fixed at $d:D = 0.8$ and the baffle angle is $45^\circ$.

Figure 8 shows the measured oxygen concentrations at 4.0 m below the stack outlet using different baffle layers. As shown in the figure, oxygen concentration for the cases with the baffles is much lower than the case without baffle. At 4.0 m below the flare outlet, oxygen concentration for the three-layer baffle case can be 5% lower than the no baffle case. On the other hand, oxygen concentration difference between the single-layer case and three-layer case is about 1% which is very close to the CFD simulation.

Figure 9 compares the oxygen concentrations between the experimental data and the CFD data at 6.0 m below the stack outlet which shows close agreement between each other.

4.2.2 Effect of throat area ratio
In this test model, conditions tested include cases with throat area ratio of 0.6 and 0.8. The baffle angle is maintained at $45^\circ$. 
Figure 10 shows the measured oxygen concentrations at 4.0 m below the stack outlet under different throat area ratio. In both cases, the experimental measurements are in close agreement with the simulation data. As is shown in the figure, a smaller throat area ratio does lead to a lower oxygen concentration and therefore a safer working condition.

However, in engineering practice, one also needs to reduce the utility cost. As shown in Figure 10, for the d:D=0.8 condition, the test and simulation results show that the oxygen concentration at 4 m below the flare stack can be kept below the 6% when the purge nitrogen flow rate is 0.024 m/s. This is already within the safe range. A higher purging speed is therefore not needed.

5. Conclusion
For typical engineering projects, the value of purging speed for dynamic seals is usually decided based on engineering experience. In this paper, the simulation experiment studies are carried out to study the characteristics of the dynamic seals. The following conclusions are drawn:

1) Both simulation and experimental results show that the baffle of the dynamic seal can reduce the oxygen concentration significantly. With the installation of the seal, air ingress can be effectively blocked under certain purging speed.

2) Both simulation and experiment have proved that oxygen concentration in the flare header drops to a certain value (about 5%-6%) and then tends to be stable. If a lower concentration is required, a larger purge speed should be used. Therefore, in the engineering design, the safe economic flow rate can be determined according to the actual working conditions of the flare exhaust gas.

3) The stack diameter and throat area ratio are two important parameters for controlling the oxygen concentration below the seal baffle. CFD simulation can be used as a tool to compute the appropriate purging speed. The simulation data has been validated against the experiment measurements and close agreement has been achieved. This provided strong basis for engineering design.

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