Application of Plume-Cooling Technology To Solve a GTG Impingement Problem: A Case Study

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Summary
Exhaust plumes from generators, pumps, and compressors aboard offshore platforms pose a hazard to crew and equipment. Mitigation for exhaust-plume impingement has traditionally been achieved by locating the exhaust uptake away from sensitive areas of the platform by use of long horizontal duct runs, by use of a very tall exhaust stack (> 20 m), or by some combination of the two. These solutions result in an exhaust system that is complicated to design and adds significant weight to the platform. A more-practical and -weight-efficient alternative exists in the form of plume cooling.

Plume-cooling technology has been in use for more than 40 years on military ships for the purpose of infrared (IR) -signature suppression and for the protection of sensitive weapons and communications systems that would otherwise be damaged by hot impinging exhaust gases. The operating principles of a plume cooler for application to the offshore oil industry are the same as for a military ship. The use of a plume cooler allows for a more-compact and -lightweight exhaust, but, surprisingly, this technology has begun to be applied on offshore platforms only within the past couple of years.

The authors of this paper have more than 28 years of combined experience in the design and manufacture of plume coolers for diesel and gas-turbine engines. In this paper, the authors present a typical plume-impingement problem aboard an offshore platform—an LM2500 gas-turbine generator (GTG) that is located centrally in close proximity to the helipad, derrick, and deck crane. By use of computer simulation tools that they have developed for plume-dispersion analyses on military ships, the authors present the predicted impingement impact of the baseline exhaust on areas of interest (AOIs) on the platform and the benefit of applying plume cooling. A comparison is also provided between the plume-cooling solution and the traditional solution of raising the exhaust-stack height, with weight being a main point of comparison.

Introduction
Offshore platforms have a large assortment of machines in service, including any number of diesel or gas-turbine engines. These engines provide mechanical work to drive pumps and compressors or to generate electricity, among other tasks. The compact nature of offshore platforms makes the management of the exhaust from engines a concern from a health and safety standpoint. Examples of detrimental impacts of exhaust-plume impingement include:

- Heating of machinery on drilling derrick, causing failure
- Heating of crane ropes, causing dryout of interstrand lubrication, which eventually results in premature failure
- Ingestion of exhaust gases by other machines or ventilation systems, causing loss of performance or dangerous exposure to exhaust gases

• Warming of air over the helipad, causing a sudden change in aircraft performance and possible loss of control
• Direct exposure of workers to elevated air temperatures and dangerous concentrations of carbon dioxide (CO₂) and carbon monoxide (CO)

The level of risk for the preceding impacts depends on the type and power output of the engine. Gas-turbine engines are particularly prone to impingement problems because of their high exhaust temperatures (> 500°C) and large volumetric flow rates. The diameter of the exhaust uptake and its proximity to AOIs on the platform also play an important role in the probability and severity of impingement impacts. Thus, platform designs that have their gas-turbine engines located centrally tend to put many areas of the platform at risk.

Up to this point, the standard practice for reducing the risk associated with exhaust-plume impingement has been to locate the exhaust-duct exit as far away from sensitive areas as possible, or to extend the exhaust duct vertically upward until all the AOIs are below the duct exit (Fig. 1). Either of these two solutions, although effective, can result in long exhaust-duct runs with associated support structure, which adds weight to the platform.

There is another solution to the plume-impingement problem, and that is the use of plume-cooling technology. Plume cooling has been used successfully on military ships for more than 40 years as a means of reducing the IR signature of the ship. A ship’s engine exhausts are the primary source of heat absorb, and thus any reduction in the temperature of visible metal or plume will reduce the detectability of the ship in the IR band (Thompson et al. 1998).

Another advantage of the use of plume cooling aboard a ship is that the temperature of mast-mounted sensors and communications equipment is lower in the event that the plume impinges upon them. An example of plume-cooling use on a military ship is the USS Makin Island (LHD-8), shown in Fig. 2. This ship class was originally powered by steam turbines, but the eighth ship was converted to gas-turbine propulsion, which greatly increased exhaust-gas temperatures, and thus required plume cooling to protect equipment on the ship’s two masts.

At the time this paper was written, the authors were not aware of any plume coolers in service aboard existing offshore facilities. Currently, there are three new platform constructions that have plume coolers installed on their GTGs: Chevron Big Foot, ExxonMobil Hebron, and Statoil Gina Krog. An explanation for why plume coolers have not been used more frequently to solve impingement problems may be as simple as designers are not aware that the technology exists. Bringing the benefits of plume cooling to the attention of designers and operators is the primary purpose of this paper.

Plume coolers are simple air/air ejectors that passively draw in cool, ambient air and mix it with the exhaust gases before they exit the device (Birk and Davis 1998). Fig. 3 illustrates schematically how a typical plume cooler functions. The technology is scalable to any size of exhaust. Development of the technology for use aboard military ships has resulted in a very compact and lightweight design that
The impact of the GTG exhaust on the AOIs has been quantified by use of the proprietary plume-trajectory analysis code PLUMTRAJ, developed by W. R. Davis Engineering Limited (Davis). The method is based on the empirical correlations of Baham and McCallum (1977) and Blevins (1984), which predict the trajectory and centerline temperature of an exhaust plume in a cross wind. These correlations are based on full-scale sea trials of a number of military ships, and have been more recently validated by Davis (Thompson and Brooking 2002).

This empirical method has advantages for this type of analysis over other computational methods, such as computational fluid dynamics (CFD), because the computing resource demand is very low. In a matter of days, it is possible to consider hundreds of different conditions, including wind speed, wind direction, exhaust-flow properties, exhaust diameter, exhaust angle, AOI location relative to exhaust exit, and ambient conditions. The ability to consider such a large number of input conditions in a short period of time is well-suited for application to offshore platforms. Surprisingly, however, plume cooling has only begun to be used in the petroleum industry within the last couple of years. The objective of the case study summarized in this paper is to present a computer simulation that is based on the comparison between plume cooling and the conventional petroleum-industry solution for plume impingement, so that the potential of this beneficial technology might be better understood.

Simulation Methodology
To quantify the benefits of plume cooling, a case study has been performed using a generic-offshore-platform (GOP) model. The model has been designed to combine some of the common features that have been encountered on new platforms over the past couple of years. A rendered view of the GOP model is provided in Figs. 4 and 5. Included in the model are three of the most common AOIs on an offshore platform: a drilling derrick, a deck crane, and a helipad. Also shown in the figure are some dimensions relative to the GTG exhaust and the location of the points used to discretize the AOI geometry for use in our analysis model. For this case study, the GTGs are assumed to be a pair of General Electric LM2500s.
the North Sea off the coast of Norway are used. Wind data are extracted from Dagny Field – Metocean Design Basis (2011). Fig. 7 is a contour plot representing the discretized probabilities of the various wind speeds and directions, corrected for the height of the exhaust stack above sea level.

PLUMTRAJ produces, as an output, the predicted temperature at each AOI discretization point for the user-defined environmental and engine conditions. The temperature prediction is provided for an array of wind speeds and directions. These data can be used directly or further reduced into a temperature-exceedance plot (TEP). A TEP combines the predicted temperature results with the corresponding probability from the historical wind data.

The result is a plot that shows how likely it is for the temperature at a particular AOI to be in excess of some specific temperature. An example TEP is shown in Fig. 8. It presents the results of a plume-trajectory analysis on a military ship with gas-turbine-exhaust impingement on a nearby mast. From this plot, one can see that with the baseline exhaust configuration, the temperature at the mast is predicted to exceed a limit temperature of 60°C approximately 73% of the time. The improvement in the probability of impingement above the limit temperature between the different configurations is also evident by use of the plot.

Another advantage of this method is that, unlike some fire- and smoke-propagation models used by the petroleum industry for trajectory studies, this method captures the three fundamental zones of every exhaust plume: turbulent jet, transition region, and buoyant plume. These three zones are illustrated in Fig. 6 for a typical LM2500+ exhaust plume under 100% engine load on an International Organization for Standardization (ISO) standard day and a 10-knot cross wind. The behavior of the plume differs greatly in each zone, such as the rate at which the plume rises per unit of horizontal distance, and the rate at which the centerline temperature decays with distance from the stack exit. Any computational model that is used to predict the impact of plume impingement on the platform must take this plume behavior into account.

PLUMTRAJ uses historical wind data, wind speed, and wind direction as inputs to the model. Use of the historical data allows for the probability of impingement to be quantified in conjunction with the location and temperature. For this case study, the wind data for the North Sea off the coast of Norway are used. Wind data are extracted from Dagny Field – Metocean Design Basis (2011). Fig. 7 is a contour plot representing the discretized probabilities of the various wind speeds and directions, corrected for the height of the exhaust stack above sea level.

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The analysis results from this case study are presented in the form of TEPs, one for each major AOI (derrick, crane, helipad) and for each exhaust type (baseline, plume cooler).

**Acceptance Criteria**

To be able to determine whether or not an exhaust configuration is acceptable, a set of acceptance criteria has been defined. The main criterion of concern is the temperature at each of the AOIs. On the basis of the various standards that we have encountered, the following set of acceptance criteria has been set:

- The impingement temperatures in the area of the derrick shall be less than 80°C.
- The impingement temperatures in the area of the crane and its ropes shall be less than 60°C.
- The impingement temperatures within the helipad’s 30-m-high-flight envelope should be less than 2°C above ambient (target), and shall be less than 50°C absolute (threshold) (CAP 437 2013; NORSOK Standard C-004 2013).

For the purposes of this trade-off study, the objective is to meet the preceding temperature criteria 100% of the time. On a real platform, it may be acceptable to achieve these requirements with less certainty, addressing the allowable small percentage of temperature exceedance events by managing work flow on the platform (i.e., not working in areas when temperature is expected to be exceeded).

**Exhaust Configurations**

For this case study, two exhaust configurations have been considered—a straight round uptake and a dual-split plume cooler. The straight uptake is referred to in the analysis results as the baseline, and is typical of the gas-turbine exhausts used on offshore platforms (see Fig. 1). The duct has an exit diameter of 3.0 m and is oriented vertically. The plume cooler is modeled after a design that has been installed recently on two different offshore platforms—Chevron Bigfoot and ExxonMobil Hebron. This splits the exhaust flow evenly in two, and is sized to provide the following performance:

- Static backpressure = 25 millibar (mbar).
- Plume average exit velocity = 30 m/s.
- Plume average exit temperature = 200°C.
- Exit diameter (each branch) = 2.5 m.

The plume cooler is also oriented vertically. The splitting of the exhaust duct into two exits has been done to take advantage of a property of plumes: The rate of decay of centerline temperature with downstream distance scales with stack diameter. Thus, by splitting the exhaust in two, the exit diameter is smaller, increasing the effective distance to the AOIs and reducing impingement temperatures.

A photograph of plume coolers on an existing platform is provided in Fig. 9. The plume coolers shown in Fig. 9 differ slightly from the schematic in Fig. 3 in that there is a cone-shaped skirt covering the air gap between the nozzle and mixing tube. The purpose of the skirt is to provide wind blockage at the air gap, ensuring a constant level of performance over a large range of wind speeds.

Both exhausts were varied in height as part of this case study. Four exit heights above the gas-turbine enclosure were considered: 10, 20, 30, and 40 m. The straight uptake was assumed to have a constant cross section over its entire length, but the plume cooler was assumed to be a fixed length of 10 m, with straight uptake sections added ahead of it to achieve the desired exit height.

**Analysis Results**

The results of the case study are presented in the remainder of this paper. The results have been broken up by AOI and by exhaust configuration.

**Crane: Baseline.** The baseline analysis of the crane shows the impingement of the exhaust plume to occur for all stack heights except for the 40-m-tall stack. The TEP for the baseline exhaust-plume impingement is shown in Fig. 10. It shows how the plume impingement on the crane and the crane ropes remains above 60°C with the baseline exhaust, until the exhaust stack is taller than the height of the crane.

The impingement on the crane occurs with a very high probability, as well, particularly for the 20-m-tall exhaust stack, with a predicted exceedance occurring for more than 10% of the year (35 days). The probability of exceedance becomes progressively lower as the exit height of the stack is increased.

**Crane: Plume Cooler.** The plume-cooler analysis for the crane impingement shows that the plume cooler reduces the impingement temperature to below the 60°C limit for all stack heights and wind conditions. This represents a significant improvement in the safety and operation of the platform. The plume-cooler crane-impingement predictions are shown in Fig. 11.

**Derrick: Baseline.** The baseline analysis of the derrick shows the impingement of the exhaust plume to occur for all stack heights. The drilling derricks on most platforms are the tallest structures, to accommodate the required depth to the drill floor, and it is
unlikely that it would ever be practical to extend the exhaust stack high enough to eliminate the exhaust plume. For the GOP studied in this paper, the only practical way to meet this requirement for all conditions (0% probability of occurrence) is to place the exhaust exit above the 30-m helipad flight envelope.

When the absolute local ambient-air-temperature limit of 50°C is considered, the percentages of exceedance are reduced but not eliminated. The 10-m stack will still exceed 50°C more than 5% of the time (18 days per year), and the 20-m stack will exceed more than 4% of the time (14 days per year).

**Helipad: Plume Cooler.** The exhaust-plume-trajectory analysis for the plume-cooler exhaust stacks shows how the safety risks at the helipad are minimized or eliminated when using a plume cooler. The analysis results are shown in Fig. 15.

When the analysis results are compared with the acceptance criteria, it can be seen that the exhaust temperature still exceeds the 2°C-above-ambient target set by the standard, but the percentage of time the temperature exceeds the limit is reduced. In comparison with the baseline exhaust, the percentage of time that the temperature will exceed 2°C for the 10-m stack height is reduced from 8 to 6% (from 29 to 22 days per year). When considering the 20-m stack height, the improvement is more significant, with the percentage of time the plume exceeds the temperature target being reduced from 8 to 1.5%, or a change from 29 to less than 6 days per year.

When the absolute local ambient-air-temperature limit of 50°C is considered, the probability of exceedance with the plume cooler is reduced to zero. This means that for any wind condition that causes the plume to pass through the helipad-avoidance region, the plume will never exceed 50°C when a plume cooler of any height is used.

**Derrick: Plume Cooler.** The use of a plume cooler for the reduction of the derrick impingement is effective for all exhaust-stack heights and wind directions, bringing the predicted derrick temperatures to below 80°C in all cases. The TEP results for the plume cooler on the derrick are shown in Fig. 13.

**Helipad: Baseline.** The exhaust-plume-trajectory analysis for the baseline exhaust stacks shows the safety risk that exhaust plumes present to helicopters during landing and takeoff (see Fig. 14). The baseline exhaust exceeds the 2°C-above-ambient target by a large margin, and does so 8% of the time (29 days per year) for both the 10- and 20-m stack heights. Once the exhaust-stack height is increased above the height of the 30-m helipad-avoidance region, the exceedance is eliminated. It should be noted that on an offshore platform, moving the GTG exhaust far enough away horizontally from the helipad to meet the 2°C-above-ambient requirement is not practical because of the large distances involved. For the GOP studied in this paper, the only practical way to meet this requirement for all conditions (0% probability of occurrence) is to place the exhaust exit above the 30-m helipad flight envelope.

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Simulation-Result Validation

Confirmation of exhaust-plume trajectory and temperature in full scale on an offshore platform is a very challenging technical problem. Because there is no control over wind speed and direction during the testing, a wide area must be instrumented and a large number of sensors used to be sure that the centerline of the plume is being captured. The use of thermography (thermal-imaging cameras) can help to simplify instrumentation, but it does not eliminate the problem of having no control over the plume’s trajectory during testing. It is no surprise, then, that there are few if any measurement data available from an offshore platform that can be used to validate the plume-dispersion models in use today. The authors’ confidence in the predictions presented in this paper stem from the fact that the methodology used is based on full-scale measurements from ships. In a ship trial, there is control over the direction and speed of the relative wind, allowing for a much-more-controlled experiment. Additional information regarding the validation of the method used in this paper against ship-trial data is available from the authors upon request (Thompson and Brooking 2002).

The empirical method used in this paper is very useful for considering a large array of conditions and providing information to help make more-informed decisions regarding what the best solution is to solve an impingement problem. Eventually, a more-detailed analysis would be performed to confirm the predicted performance of the plume cooler and examine design aspects that cannot be handled by the empirical method such as flow recirculation or the impact of obstructions. Fig. 16 provides an example of how maximum predicted temperatures for a plume-cooler installation on an actual offshore platform compare between the empirical method and the commercial CFD code ANSYS® Fluent (2015). Good correlation between the two is often observed, providing further confidence in the empirical method.

Weight Impact

The analysis of the exhaust-system weight has been completed by use of known standard weights for the typical baseline straight-uptake exhaust system and the average system weight of the currently in-service Davis plume-cooler systems. Fig. 17 illustrates the general appearance of each installation.

The typical baseline exhaust for the GE LM2500 engine is a 3-m-diameter, double-walled, stainless-steel exhaust duct with a carbon-steel external support structure. The design considered for the straight exhaust stack comes in 8.5-m increments with support structure. Any remaining duct length above the final full 8.5-m section has been cantilevered without the need for additional support structure.

The plume-cooler system is 10 m and includes associated support structure. For exhaust systems taller than 10 m, we have assumed that the baseline exhaust duct is used up to the inlet of the plume cooler, and the baseline support structure is used for the full length of the baseline system.

The weight of the baseline system is based on experience and drawings from known installations. The double-walled exhaust
duct is estimated to weigh 9000 kg per 8.5-m section, and the support structure is estimated to weigh 3000 kg for the top 8.5-m section and 6000 kg per 8.5-m section below that.

The plume-cooler weight, which is based on currently in-service designs, is 11 000 kg. This includes internal insulation and support structure.

By use of the component weights as described, we can estimate the weight of each height of exhaust stack for the plume-cooler and baseline systems. The weight estimates are summarized in Table 1. The plume cooler has only been estimated for the 10- and 20-m system heights because it is not necessary to have a plume cooler taller than 20 m to achieve all of the acceptance criteria. For most cases, it is possible to achieve the necessary impingement temperatures with a plume cooler height of only 10 m. Note that the weights in Table 1 do not include any impact on underlying rig structure resulting from the weight of the exhaust installation.

It can be seen that by using a plume cooler and reducing the height of the exhaust stack, there will be a significant weight savings. For example, if a 40-m-tall baseline exhaust stack is required to achieve safe impingement levels, and this can be replaced with a 10-m-tall plume cooler, there could potentially be more than 56 000 kg in weight savings per engine.

### Engine-Performance Impact

The advantages provided by use of a plume cooler come at a cost to the performance of the engine upon which it is installed. It is the momentum of the exhaust gases that provide the work to draw cool, ambient air into the plume cooler. As a result, the engine sees the plume cooler as an exhaust backpressure. The plume cooler considered in this paper imposes a backpressure of 25 mbar on the GTG, but it can be designed to be any value. Adding backpressure to an engine’s exhaust results in a reduction in power output for the same fuel flow. This impact must be accounted for when integrating any engine with a plume cooler.

### Conclusions

This paper presents a case study for the prediction of GTG plume-impingement temperatures on a number of different AOIs aboard an offshore platform. The analysis shows that although some of the temperature targets can be met by simply raising the height of the exhaust-stack exit, it is far more effective to use a plume cooler. Superior plume-impingement temperatures can be achieved, with lower probability of occurrence, by use of a plume cooler that is significantly shorter than a straight uptake. This presents a large potential for weight savings on the platform.

Although not discussed specifically in this paper, plume coolers are equally effective at reducing the concentrations of exhaust-gas constituents such as CO and CO₂. This should be considered as yet another benefit of these devices.

### References


### SI Metric Conversion Factors

| mbar × 1.0 × 10² = Pa |

*Conversion factor is exact.*

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