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Report

Field Measurement of BC Emissions from Rolvsnes Well Test Flare

An empirical measurement of particulate emitted from a well test flare to generate a BC emission factor.

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Rolvsnes well test flaring with the COSL Innovator drill rig 6th-9th August 2018

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SINTEF

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Report

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ABSTRACT
BC (smoke particulate) was measured in the emissions from the Rolvsnes well test flare from the 6th - 9th of August 2018. Approximately 90% of the measured particulate matter was in the PM 1 range (1 micron in diameter and smaller). Smoke particulate this small can stay airborne for considerable time.

The flare emissions contained little visible smoke. An instrumented hexacopter drone was utilized to collect smoke plume data that would enable a calculation of a BC emission factor. A constant feed rate of 620 m3 of oil and 81,000 m3 of natural gas per day was reported for the Rolvsnes well test flare. The calculated BC emission factor derived from an array of transects through the well test flare smoke plume ranged from: 0.42 to 0.84 kg BC per tonne of combined oil and gas; and 0.48 to 0.96 kg BC per tonne of oil (this emission factor, relative to oil, is conservative as it incorrectly assumes no contribution of gas combustion or to a lesser extent platform diesel combustion to BC).

No visible evidence was observed that would indicate any oil fallout from the flare to the sea surface.

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1 Background

SINTEF was contacted by Lundin (first email dated 5th April 2017) regarding measurement of soot and Black Carbon (BC) from flaring in relation to an oil well test flaring. The project was sponsored through BASEC. The well test measurements would be used to calculate an oil flare emission factor for BC. BC emissions of the Particulate Matter (PM) size centred around 2.5 microns in diameter (PM2.5) in the arctic environment contribute to enhanced melting of snow and ice via increased absorption of solar radiation (McEwen and Johnson, 2012). Norway is a participant in an international effort to limit short-lived climate forces such as BC, methane and aerosols.

During the NOFO Oil-on-Water field trial in June 2016, drones were successfully used for air sampling of particles and hydrocarbons during *in-situ* burning of oil. A SidePak™ Aerosol Monitor was used for real time monitoring of $PM_{2.5}$ (particles up to 2.5 microns). Two years later, during the NOFO Oil-on-Water field trial in 2018, an enhanced array of instruments was flown by drone through smoke plumes associated with *In-situ* burning of oil. The experience gained during NOFO's Oil-on-Water field exercise was the basis for the field approach utilized for this project. Maritime Robotics, a sub-contractor to SINTEF, provided the drones and pilots.

2 Objectives

The principle objective of this project was to calculate an oil well test flare emission factor for BC. Limited empirical data exists for this this type of emission (McEwen and Johnson, 2012; DNV GL, 2015). Due to differing oil compositions, differing gas to oil ratios, and different flaring equipment and operational technique, BC emission factors can widely vary (McEwen and Johnson, 2012). The objectives of this project were to gain a greater understanding of the actual amount of BC emitted from an oil well test that utilized a state-of-the-art flaring system. According to the Norwegian Environmental Agency Report M135, there is a need for local monitoring of BC and to establish measurement methods for documenting the emission of BC. This should include emissions of BC from oil well flaring operations. At the specific request of the Client, a secondary objective was to document observations associated with flare emission fallout to the sea surface.

3 Rolvsnes well test flare

The Rolvsnes well test flare operations were performed on the rig COSL Innovator by Expro AS. The well test unit is a conventional test unit with a test separator and separate flow paths for oil and gas sent to a flare boom for combustion. The oil flow is combusted using a state-of-the-art burner (Sea Emerald Burner). The burner is designed to ensure fast and efficient burning of the oil, thereby minimizing the formation of black carbon and fall out of hydrocarbons. This is obtained by atomization of the oil to as small droplets as possible and ensuring maximum amount of air available for the combustion. The burner has been confirmed to operate with 99,993% efficiency at a wide range of conditions.

The oil from the Rolvsnes well is expected to be similar to the Edvard Grieg (Luno) oil. This oil is characterized as a medium paraffinic crude oil with a density of 850 kg/m^3, with a medium wax content and low asphaltene content.

4 Methods Utilized to Collect Field Data

The planned approach to derive an empirical calculation of an applicable BC emission factor involves correlating oil and gas flare feed rates to calculated BC emission discharge rates. The oil and gas flare feed rate data were supplied by the client and were reported to be constant during the entire monitoring period. The calculation of BC discharge rates included:

- measurement of wind speed in the proximity of the flare emission plume through the use of a drone-mounted anemometer;
- measurement of particulate matter (PM) concentration by utilizing a drone-mounted DustTrak aerosol monitor that flew transects through the flare emission plume; and
- measurement of flare emission plume cross-sectional area at the transect locations of PM data

Measurement of the flare emission plume cross-sectional area was conducted by analysing the GPS record of the drone where smoke particulate was detected. Transects were designed to yield useful information pertaining to the smoke plume cross-sectional dimension and average concentrations.

However, since the feed rate of carbon to the flare was known, a different and more straight forward approach to calculate a BC emission discharge rate was also conducted. The focus of this alternative approach was to measure the proportions of carbon in the smoke that existed as CO, CO_2, and BC. The portion of burned carbon that ended up as BC times the feed rate of carbon to the flare yields an emission discharge rate.

To complete the secondary objective of documenting observations associated with flare emission fallout to the sea surface, visual observations were conducted of the sea surface below and down-current from the flare from a MOB boat, from the support vessel, and from the aerial drone video footage. An infrared camera was also utilized to scan the sea surface for evidence of potential flare fallout. Pre-weighed oil absorbent and Teflon pads were also brought to sample any observed flare fallout material that landed on the sea surface.

4.1 Instrumentation

The drone utilized for this project was a DJI Matrice 600 Pro, a hexacopter drone. Drone-mounted instrumentation utilized for obtaining data from the smoke plume included:

- an Extech Instruments Hot Wire Thermo-Anemometer with Datalogger Model SDL350
- a TSI DustTrak DRX Aerosol. Monitor Model 8534
- an MSA Escort Elf Pump
- a Dräger X-am 5600 gas meter arrayed with electrochemical sensors to measure O_2, CO, and SO_2 and a dual infrared sensor to measure CO_2 and Combustible (LEL) gasses.

Figure 4.1 *View of the hexacopter drone instrumented with an anemometer and a DustTrak aerosol monitor. Instrument sensors or intake to the instrument sensors that were utilized for collecting smoke plume data were placed on a support arm upwind of the drone's propeller downwash.*

Figure 4.2 View of the hexacopter drone instrumented and both Maritime Robotics drone pilots. A hood-screen was used to pilot the drone. The stack of pallets reduced magnetic interference to the drone's compass.

Maritime Robotics was sub-contracted to SINTEF and was responsible for the drone operations. Maritime Robotics provided:

- One multicopter with capability of carrying sensor systems up to 2 kg
    - Video recording
    - Live Video
    - Custom integrated payload from SINTEF
- One spare multicopter that can replace the above capacities
- Two trained and certified drone-operators with required training and necessary licenses from the Civil Aviation Authorities (max 12h daily duty)
- Air-space preparations and flight mission planning
- Integration of customer chosen payload
- Post-processing of data and delivery of data to SINTEF after mission

4.2 Approach to flying transects through smoke plume

The main goal of flying the instrumented drone through the smoke plume was assess the average concentration of smoke particulate present and to obtain enough information to calculate the cross-sectional area of the smoke plume. The main difficulty encountered with this effort was that the smoke particulate concentrations were too low to readily see. Therefore, the challenge was determining where the smoke plume was located. Most of the transects flown through the smoke plume were flown at a distance between 150 to 200 meters downwind of the flare. A live temperature reading that was relayed back to the drone pilot assistant provided the feedback that was used to determine when the drone entered and left the smoke plume. As a result of conducting a series of flights through the smoke plume, it was determined that the easiest approach involved starting with the drone located above the center of the smoke plume and then conducting a vertical transect downward, followed by two more vertical transects located approximately 20 meters to either side of the initial transect. While flying these transects, the drone assistant noted the approximate altitude when the drone apparently entered and left the smoke plume. Subsequently, horizontal transects were conducted starting with the center altitude and then completing additional ones above and below with spacings approximately 20 meters apart until no contact with the smoke plume was detected during a horizontal transect. Another useful strategy was to fly the drone well outside of the smoke plume to create very clear and distinct transects, and to pause for 5 to 10 seconds between transects to obtain another stationary wind speed reading.

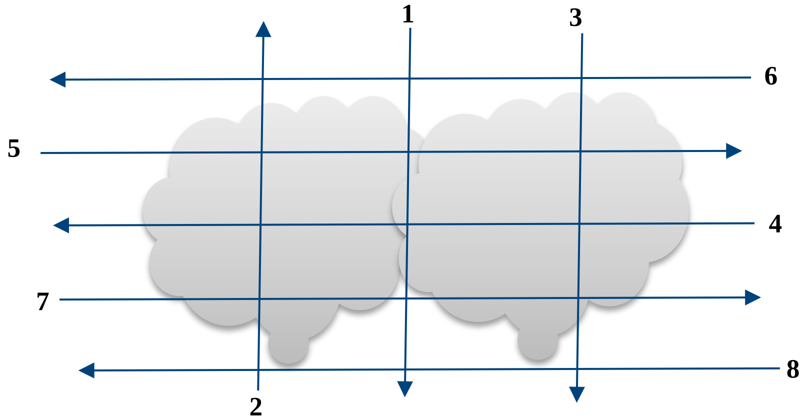

Figure 4.3 Schematic of a successful smoke plume transecting approach.

Figure 4.4 View from drone as it approaches the well test flare smoke plume shortly after takeoff from the Skandi Gamma support vessel.

Figure 4.5 Close up view of flare with smoke plume and drone in background.

Figure 4.6 *On the left, view from drone depicting the typical position of the Skandi Gamma support vessel relative to the flare. On the right, view of the hexacopter drone heading back to the support vessel with the flare in the background.*

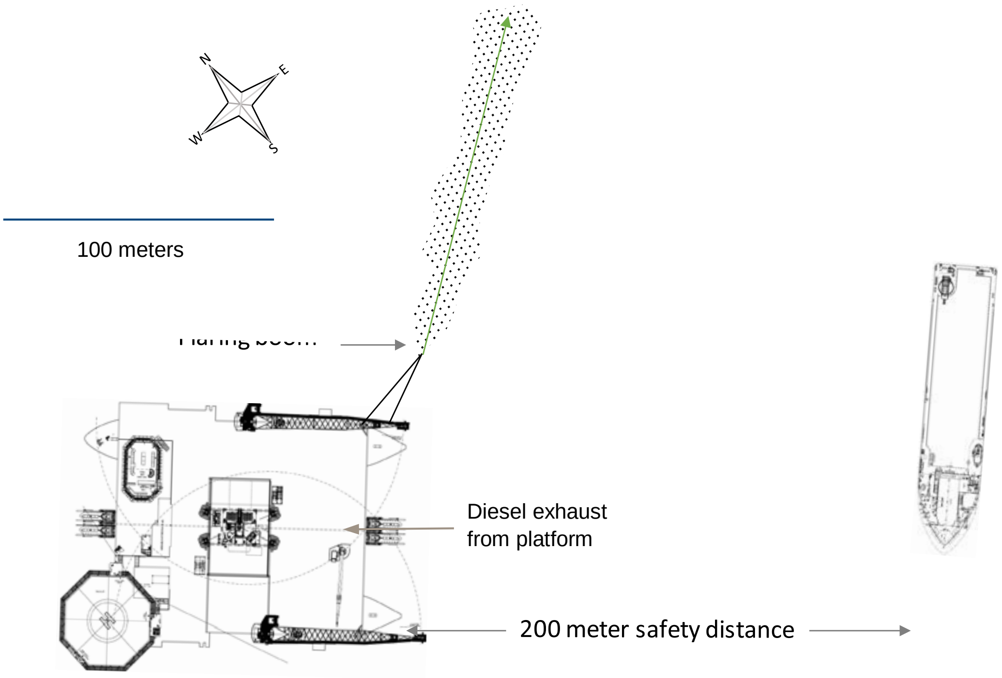

Figure 4.7 *Typical orientation of Skandi Gamma compared to COSL Innovator during drone operations.*

5 Field Data Summary

Field data was collected from over a four-day period, from 06/08/18 through 09/08/18. A support vessel, the Skandi Gamma (95 meters in length), provided access to the well test flare emissions. Drone flights were limited to wind speeds below 8 meters per second. The well test flare reportedly had a constant feed rate of oil and gas throughout this period. Sampling was limited by weather conditions, daylight, and availability of the support vessel. A total of 15 drone flights were conducted over this period. These 15 flights are summarized in Table 5.1.

Table 5.1 Drone Flight Summary

Date	Start Time	Flight #	Drone GPS	Anemo-meter	Dust-Trak	Gas Sensors	PM Filter	PM 2.5 (mg/m^3)	Excess CO_2 (ppm)	Comments*
6/8/2018	19:18	1	X	X	X					Transects not well separated. Needed to extend transects further outside plume.
6/8/2018	20:15	2	X	X	X					2 decent transects
7/8/2018	8:46	3	X	X	X					Some nice transects
7/8/2018	9:51	4	X	X	X					Nice Transects
7/8/2018	14:41	5	X	X	X		X			Loading PM Filter
8/8/2018	7:55	6	X	X	X	X				Missed smoke plume
8/8/2018	8:25	7	X	X	X	X		0.046	221	3 decent transects
8/8/2018	8:54	8	X	X	X	X				1 transect
8/8/2018	12:21	9	X	X	X	X		0.145	380	Nice Transects
8/8/2018	12:49	10	X	X	X	X		0.154	392	Many transects
8/8/2018	13:25	11	X	X	X	X		0.110	380	Some nice transects
8/8/2018	14:16	12	X	X	X		X			Part 1 loading PM filter
8/8/2018	14:43	13	X	X	X		X			Part 2 loading PM filter
9/8/2018	8:16	14	X	X	X	X		0.117	419	Best array of transects
9/8/2018	8:44	15	X	X	X	X				Few transects (wind shifted)

* The comments column in the above table generally pertain to the suitability of the smoke plume transects flown by the drone to collect enough useful data to either allow for a comparison of the proportion of carbon in the smoke plume that ended up as CO_2 or BC (which required gas sensors to be present); or to both allow for a decent measurement of the smoke plume cross-sectional area coupled with well-spaced sampling of the smoke plume for averaging BC concentrations.

5.1 Measurement of smoke parameters

This section of the report presents how each of the key parameters associated with calculating a BC emission factor was collected, as well as summarizing the data sets that were used.

5.1.1 Well test flare feed rate

The feed rate for the well test flare for the duration of our measurements was initially reported to be a constant 680 m^3/day for oil and 81,000 m^3/day for gas. The final corrected flowrates during the test were estimated to be slightly lower, around 620 m^3/day oil.

The gas flare plume will commingle with the oil flare plume. Also, during the measurement period, diesel combustion exhaust was observed from the drill rig. Daily consumption rates for diesel ranged from 31 to 37 m^3. It is possible that this exhaust stream comingled with the flare emissions. However, based on the relatively low volume of diesel and mass of gas burned (12.8% of the combined mass of oil and gas) and the low calculated BC emission factors, additional effort to assess potential contribution of the diesel or gas exhaust to the flare emission smoke plume was not made. The approximate location of the diesel exhaust from the platform is depicted in Figure 4.7.

5.1.2 Wind speed and temperature

Both wind speed and temperature were measured and logged by an Extech Instruments Hot Wire Thermo-Anemometer with Datalogger Model SDL350. The logging interval was set to 1 per second. Wind speed measurements collected from Flight 14 were used in conjunction with the smoke plume cross-sectional area calculation to derive the volume of smoke passing the flown transects. Wind speed measurement data that were utilized were limited to when the drone was relatively stationary prior to conducting a transect. The logged temperature was used in the conversion of CO_2 part per million (ppm) volume measurements into mass.

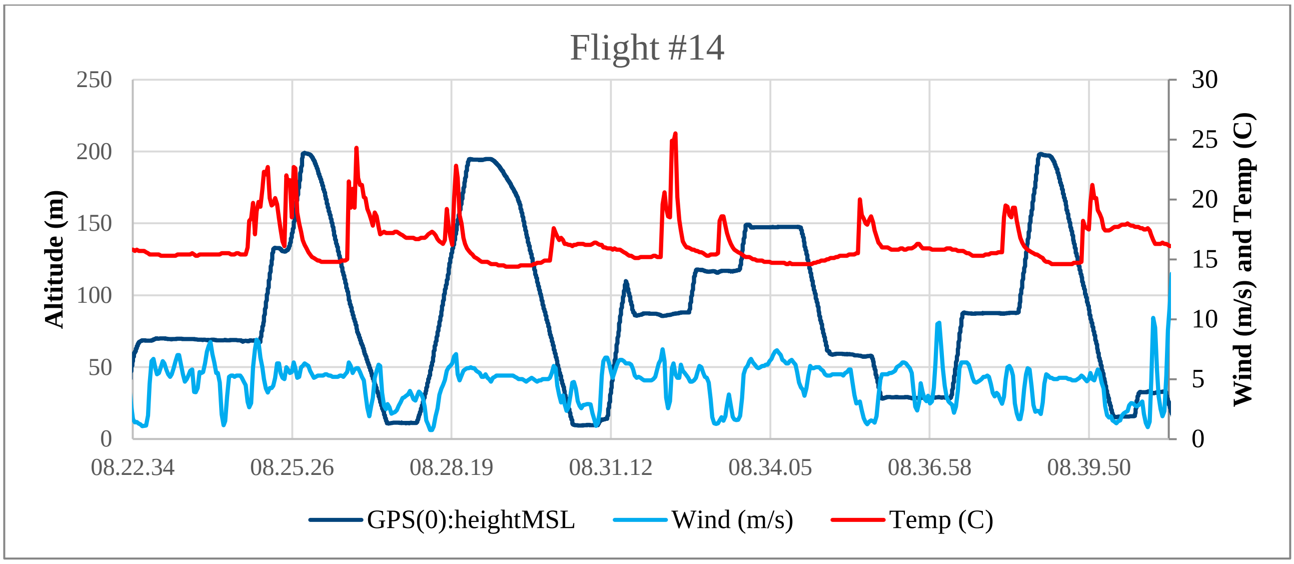

Figure 5.1 Plot of wind speed, temperature, and altitude during Flight 14. The temperature plot conveys when the drone entered and left the smoke plume.

Wind speed was also a significant limited factor as to when the aerial drone could safely fly (< 8 m/s). Information that was used to assist in determining when to fly the drone included: updated weather reports, wind readings from the bridge of the vessel, and observation of the sea state (for lack of white caps on the waves). After obtaining information from the bridge that wind conditions appeared favourable, the drone was flown to an approximate altitude of 200 meters during the first flight to assess wind speed at altitudes higher than the wind gage used by the vessel. During the first two days of sampling, wind speed was often too high, which limited the number of flights that were flown on those days. Day three had reduced wind conditions, which allowed for plenty of flights.

5.1.3 GPS positional information

Positioning information for the drone and drone-mounted equipment was logged by the optional increased accuracy GPS associated with the DJI Matrice 600 Pro hexacopter drone. A temporal resolution in excess of 10 hertz was provided to SINTEF. Figures 5.3 and 5.4 utilize GPS data to graphically represent the transects of Flight 14 that intersected the smoke plume.

5.1.4 Smoke Particulate

Smoke particulate (BC) concentrations were measured and logged by a TSI DustTrak DRX Aerosol. Monitor Model 8534. This instrument was setup to measure particulate matter (PM) ranging in size from approximately 0.1 to 15 microns and report them in the following micron size ranges: PM 1, PM 2.5, PM 4, PM 10, and Total PM at concentrations ranging from 0.001 to 150 mg/ m^3. The instrument was set to log these measurements every second.

The instrument was factory calibrated with an Arizona Road Dust standard. It should be noted that although the instrument reports mass per volume, its measurement techniques are based on size (volume) of the particulate/aerosol. As such, it is important to know the relative density of the particulate being measured compared to the factory calibration. For oil generated smoke, this particulate is approximately 2.1 times less dense than the Arizona Road Dust standard. This statement is based on comparing this specific instrument's readings with recently completed gravimetric analysis of an array of collected smoke particulate emitted from burning various crude oils and fuel oils (Faksness 2018). Two attempts were made during this field effort to collect enough smoke particulate for gravimetric analysis. However, due to the very low concentrations of smoke particulate encountered, not enough was collected to reliably measure gravimetrically. Figures 5.3 through 5.5 show plotted data of Flight 14 that includes particulate data.

5.1.5 CO and CO_2 gas measurements

A Dräger X-am 5600 gas meter arrayed with electrochemical sensors to measure O_2, CO, and SO_2 and a dual infrared sensor to measure CO_2 and Combustible (LEL) gasses was used to log gas concentrations once per second. The CO sensor has a measuring range of 0 to 2,000 ppm, with a resolution of 2 ppm. The CO_2 sensor has as measuring range of 0 to 5% and a resolution of 0.01% by volume (equivalent to 100 ppm by volume). This instrument is periodically calibrated by an outside vendor. A calibration check of 0 and 50 ppm for CO as well as 0 and atmospheric levels (approximately 400 ppm) for CO_2 was performed prior to the field effort. The response time for 90% of the reading for CO was listed as 25 seconds and for CO_2 31 seconds.

Essentially no CO was detected during these flights (less than 2 ppm).

CO_2 was detected. However, the detections were at the lower end of the measuring range (generally less than 10 times the detection level). Additionally, due to a lag in sensor response through varying concentrations of smoke, it appears likely that the CO_2 was under-reported somewhat. Attention was made to include CO_2 data where the sensor was present in the smoke plume for longer periods of time. Utilization of a CO_2 sensor with a more rapid response time would be useful.

5.2 Data summary from the flight with the best set of transects

Flight 14 conducted on the morning of the 9th of August 2018 was flown using the approach described in Section 5.1. This flight yielded the highest number of well-spaced transects through the smoke plume with a couple more bracketing it. As such, it provided the most data regarding the size and shape of the cross-sectional area of the smoke plume as well as having the most data points of smoke particulate, CO and CO_2. Figures 5.3 through 5.5 present plots of the data from this flight. Figure 5.2 depicts a significant feature, two counter-rotating vortices that exist within a rising gas plume. However, please note that Figure 5.2 is from a recently completed In-Site Burn of Oil that was conducted during NOFO's 2018 Oil on Water exercise. It is included here as the smoke concentration was much higher, making the counter rotating vortices noticeably more visible.

Figure 5.2 View from the drone of how a rising smoke plume from an In-Situ Burn of Oil divides into two counter-rotating vortices. This image was taken during NOFO's 2018 Oil on Water exercise. The plots of data in Figures 5.3 through 5.5 depict the presence of the two counter-rotating vortices that were encountered during Flight 14.

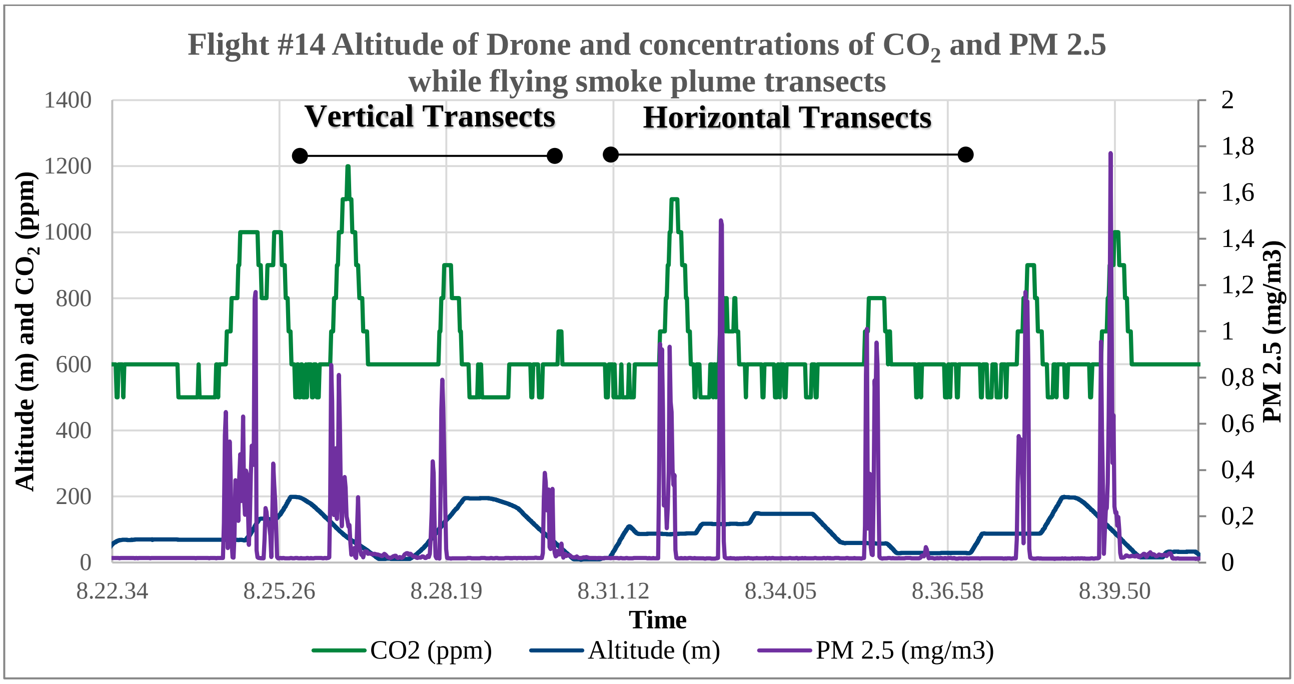

Figure 5.3 *Plot depicting drone flight 14 versus time. Note that the drone started well outside of the smoke plume and continued well past it for each transect. CO_2 exists in the atmosphere, hence the non-zero baseline.*

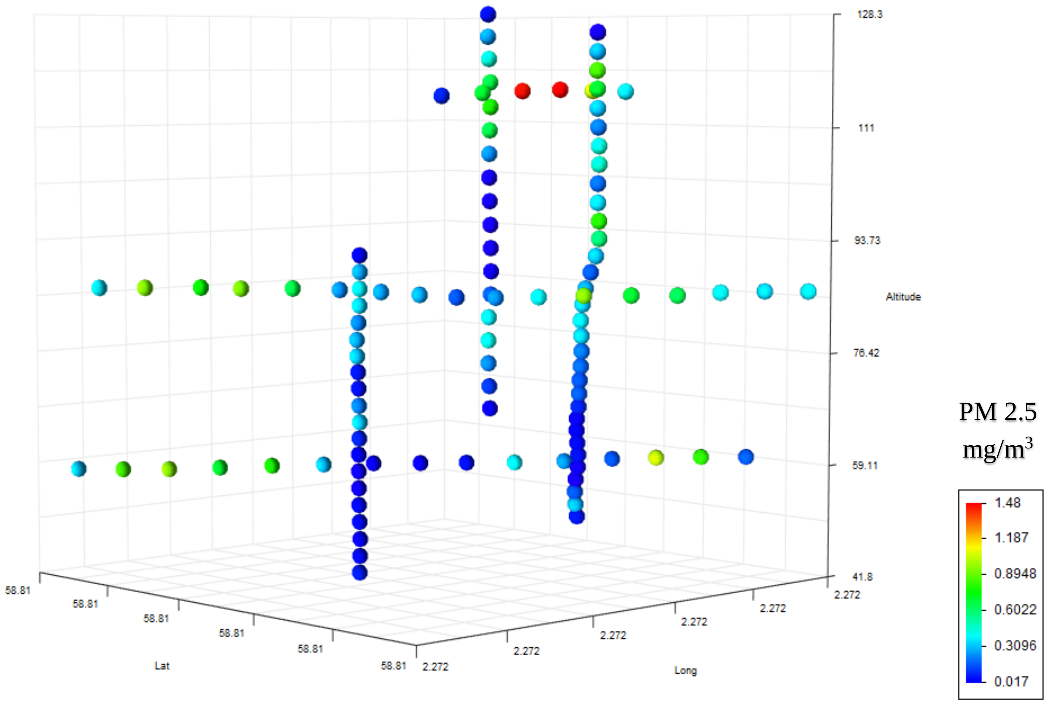

Figure 5.4 *Plot of smoke particulate (PM 2.5) along transects through the smoke plume. View looking at the cross-sectional area. The smoke particulate values represented here are in factory calibrated mg/ m^3. The intersection of the transects show general agreement with the concentrations. The concentrations of PM 2.5 along the transects match nicely with the expected presence of two counter-rotating vortices that should be present in a rising smoke plume at this distance from the source.*

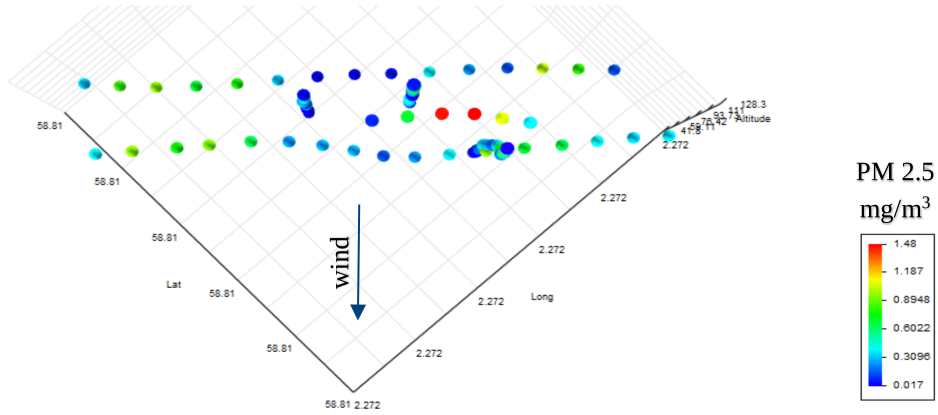

Figure 5.5 *Plot of smoke particulate (PM 2.5) along transects through the smoke plume. View from above. The smoke particulate values represented here are in factory calibrated mg/ m^3.*

All three plots depict the presence of two counter-rotating vortices. Figure 5.4 presents the best illustration. These two vortices characterize the structure of a rising smoke plume (Evans, et al. 2001). An example of which is presented in Figure 5.2. Figure 5.3 presents the timeline and transect order for Flight 14. Figure 5.4 presents a view looking at the smoke plume cross-sectional area encountered during Flight 14 where the particulate concentrations were plotted in relation to latitude, longitude, and altitude. This cross-sectional area was delineated by well-spaced transects. The intersections of the transects showed agreement with particulate concentrations. Figure 5.5 presents an overhead view looking down at the transects. Figure 5.6 shows an image taken from the drone video looking through the smoke plume to the well flare.

Figure 5.6 *View from drone while it is near the center of the smoke plume during Flight 14. The curtain of water behind the flare is designed to protect the drill rig from the radiant heat emanating from the flare.*

5.3 Observations to assess potential oil fallout from the flare to the sea surface

In the general timeframe that drone flights were being flown, observations were being made of the sea surface in the vicinity of the flare and downwind of the flare for visual evidence of potential oil fallout from the flare to the sea surface. These observations were made during each of the days spanning 06/08/18 to 09/08/18. During this timeframe, the feed rates of oil and gas to the flare were reportedly constant.

The observations were made from:

- the bridge of the Skandi Gamma, which was positioned approximately 200 meters away from the COSL Innovator
- Oil Spill Detection radar mounted on the Stand-By Vessel on location.
- high resolution (4k) drone imagery, which included the flare and the down current sea surface
- a MOB boat survey that included a close-up inspection of the sea surface below the flare and numerous down-wind transects (Figure 5.7).

In addition, to visual observation and high-resolution video, an IR camera was also utilized to scan the sea surface for evidence of potential oil fallout.

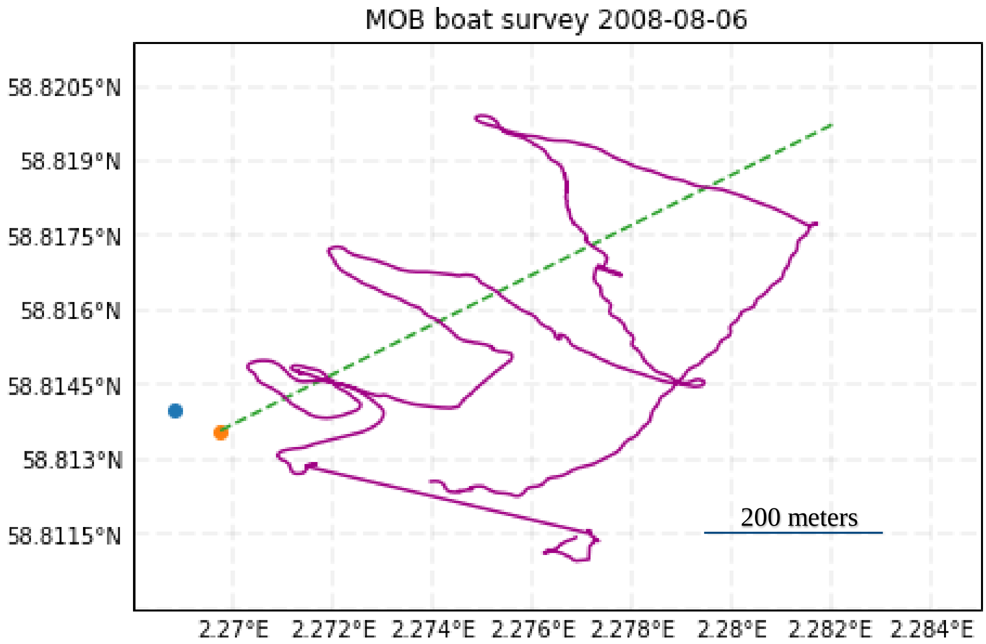

Figure 5.7 GPS track of the MOB boat inspection. The blue dot is the AIS position of COSL Innovator. The orange dot is the estimated position of the flare. The green line shows the wind direction.

As a result of the above summarized observations, no evidence of oil was observed on the sea surface.

6 Calculation of BC Emission Factor

Two different methods for calculating a BC emission factor are presented here. The first method involves comparing the rate of BC generated through volumetric means versus the rate of fuel being burned. The second method involves accounting for the mass of carbon in the flare emissions. By measuring the relative concentrations of CO, CO_2, and particulate matter in the smoke plume, a partitioning of the mass of carbon between those can be established, and thus coupled with a feed rate of carbon will yield an emission factor.

6.1 Calculation of the rate of BC generated based on volume

This was the initial approach proposed, as it was based on an approach applied to an In-Situ Burn of oil on the sea surface, where the rate of oil burning was not known. This method was referred to as the flux method for determining smoke yield by Evans et al. (2001).

The data for this calculation was collected during Flight 14, primarily because the transects were well placed to define the cross-sectional area of the smoke plume. Additionally, two counter-rotating vortices were depicted in the plotted data, which indicates that the anticipated features of this smoke plume were well represented.

Table 6.1 Calculation of mass of PM 2.5 (BC) generated based on volume and concentration calculation of smoke particulate.

Total length of transects within the smoke plume	424	m
Average PM 2.5 along transects within smoke plume adjusted by a calibration factor of 2.1	0.190	mg/m^3
Cross-sectional area of smoke plume	5,870	m^2
Wind speed	5.2	m/s
Volume of smoke per second at measurement distance from flare	30,500	m^3
PM 2.5 in smoke plume	5.82	g/s
PM 2.5 generated	503	kg/day
BC emission factor relative to the combined oil and gas feed rate	0.84	kg BC/tonne of combined oil and gas
BC emission factor relative to oil (mass of BC generated per mass of oil burned)	0.96	kg BC/tonne of combined oil and gas

6.2 Calculation of the rate of BC generated based on mass of carbon

Since the feed rates of both oil and gas to the well test flare as well as the approximate carbon mass of the oil and gas are known, an accounting of the partitioning of this carbon mass to the flare emissions will yield a rate of BC generated. Carbon that is present in oil and gas, when burned will partition into CO_2, CO, and smoke particulate. This method was referred to as the carbon balance method by Evans et al. (2001). The data for this calculation was also collected during Flight 14.

Table 6.2 Calculation of mass of C present in flaring fuel

Flare feed rate oil	620	m^3/day
Flare feed rate gas	81,000	m^3/day
Reported density of Rolvsnes Oil	0.845	kg/l
Reported specific gravity of Rolvsnes gas	0.79	relative to air
Mass of oil burned per day	524,000	kg/day
Mass of air at 20ºC at sea level	1.204	kg/ m^3
Mass of gas burned per day	77,000	kg/day
Percentage of mass that is carbon within crude oil	85	%
Percentage of mass that is carbon within natural gas	80	%
Flare feed rate of carbon (both oil and gas)	507	tonnes/day

Table 6.3 Calculation of mass of BC emitted.

Date	Time	PM 2.5 (mg/m^3)	excess CO2 (ppm)	gram CO2 per m^3	gram of C per m^3	% of carbon in smoke that is PM 2.5	% of carbon in smoke that is CO2	Mass of BC emitted per day (kg/day)	kg BC emitted per tonne of oil and gas	kg BC emitted per tonne of oil
8/8/2018	8:38:19	0.055	221	0.406	0.111	0.05%	99.95%	250	0.42	0.48
8/8/2018	12:33:48	0.173	380	0.698	0.191	0.09%	99.91%	461	0.77	0.88
8/8/2018	12:56:04	0.183	392	0.720	0.197	0.09%	99.91%	472	0.79	0.90
8/8/2018	13:31:53	0.130	493	0.906	0.247	0.05%	99.95%	266	0.44	0.51
9/8/2018	8:24:30	0.132	380	0.698	0.191	0.07%	99.93%	350	0.58	0.67
9/8/2018	8:26:19	0.146	458	0.842	0.230	0.06%	99.94%	322	0.54	0.61

The data presented here were collected from longer transects of the drone passing through the smoke plume to allow for a more full-scale response of the CO_2 sensor. The mass of BC emitted per day is based on the proportions of carbon measured within the various smoke plume transects times the feed rate of carbon to the flare. The BC emission factor presented as kg of BC emitted per tonne of oil and gas is based on the combined feed rate of oil and gas. The last column (kg of BC emitted per tonne of oil) is a conservative calculation for a BC emission factor relative to oil as it incorrectly presumes no contribution of gas combustion to BC.

7 Findings and Conclusions

Smoke particulate (primarily BC) was measured in the smoke emissions from the Rolvsnes well test flare. The size fraction reported is PM 2.5, which constitutes approximately 90% of the total PM measured. PM 2.5 is particulate matter with a diameter of 2.5 microns or smaller. The PM 1 (1 micron and smaller) data was essentially the same as the PM 2.5, indicating that approximately 90% of the total PM measured was also smaller than 1 micron in diameter. Smoke particulate this small can stay airborne for considerable time.

Based on determining the volume of smoke generated per unit time through the measurement of the smoke plume cross-sectional area and wind speed, total amounts of BC (PM 2.5) within the flare emissions were calculated. Based on this approach, two emission factors were calculated:

0.84 kg BC per tonne of combined oil and gas

0.96 kg BC per tonne of oil (this emission factor, relative to oil, is conservative as it incorrectly assumes no contribution of gas combustion or to a lesser extent platform diesel combustion to BC)

The partitioning of C within the smoke plume between CO_2, CO and BC was computed for six different transects spanning five different drone flights. CO was not detected (detection level was 2 ppm) and thus the partitioning of C into CO was considered negligible. Data from all six transects indicated: 1) that the proportion of carbon burned that became CO_2 ranged from 99.91 to 99.95%, and 2) that the proportion of carbon burned that became BC ranged from 0.05 to 0.09%. For a flaring feed rate of 507 tons of carbon per day, that translates into 250 to 472 kg of BC per day. The amount of BC generated per day based on the calculation of the volume of smoke generated per unit time (smoke plume cross-sectional area times wind speed) had a similar calculated BC mass emitted of 502 kg/day.

Based on this partitioning of C approach to measuring BC, the following ranges of BC emission factors were calculated:

0.42 to 0.79 kg BC per tonne of combined oil and gas

0.48 to 0.90 kg BC per tonne of oil (this emission factor, relative to oil, is conservative as it incorrectly assumes no contribution of gas combustion or to a lesser extent platform diesel combustion to BC)

Assumptions or limitations involved in the calculations or measurements that could significantly impact the calculations:

- DustTrak factory calibration results in a reported mass of particulate that is higher than reality, because the Arizona Road Dust standard is more dense than fine smoke particulate. Two attempts were made to collect enough particulate on filters for gravimetric analysis; however, the smoke concentration was too low to collect enough mass for analysis. Therefore, we used recently completed laboratory test data from various bulk oils where we found this instrument reported on average approximately 2.1 times more mass than what was generated. A literature review found similar calibration factors for smoke from an oil burn.
- Assumptions utilized for calculating the volume of smoke and average concentration present within the smoke plume to generate a BC emission factor did not have a significant impact as the range of BC emission factors that were calculated based simply on the ratio of BC to CO_2 bracketed the volumetric approach.
- The CO_2 sensor had a time lag and likely under reported the CO_2 concentration to a degree. Effort was made to minimize this effect, by utilizing data from transects where the drone was in the smoke plume for a greater duration of time. The potential to slightly undermeasure CO_2 would result in a slightly higher BC emission factor calculation.
- Diesel exhaust from the platform was visible and may have co-mingled with the flare emissions. That potential can result in a slightly higher BC emission factor calculation.

Observations of the sea surface near and down current from the flare revealed no evidence of oil fallout to the sea surface.

8 Recommendations

The following recommendations are made in reference to adjustments in methods for potential future field measurements of flaring emissions.

- A BC emission factor can be calculated by both methods utilized in this study: measuring amount the of BC generated versus balancing carbon emissions of CO, CO_2 and BC. Conducting both can assist in validating the results.

- If the smoke plume is difficult to see, then the smoke particulate concentrations will be too low to collect enough for gravimetric analysis.

- Use a fast response CO_2 sensor that is spanned for lower concentrations.

- If conducting transects to assess smoke plume cross-sectional area, conduct them in wind conditions that are in the upper end of safe drone flying. Higher wind speed deceased the altitude of the top of the smoke plume, which enabled transects to be completed more readily.

- Follow the general transecting approach of Flight 14 for this study, as it yielded the best data set for calculating the cross-sectional area of the smoke plume.

- Drone data provided at a temporal resolution of 1 hertz is sufficient.

- Time stamp onto the drone video would assist with analysis.

- According to the Norwegian Environmental Agency Report M135, there is a need for local monitoring of black carbon. As such, it is recommended to conduct further monitoring events that would include different fuel ratios, feed rates, and flaring equipment.

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