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Performance testing and analysis of vertical ambient air vaporizers

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Abstract. Ambient air vaporizers are used to regasify cryogenic liquids at extremely low temperature (below -153°C). Frost formation occurs on it due to large temperature difference between ambient air and cryogenic fluid. Frosting induces additional load on equipment and reduces its heat transfer effectiveness. Hence, mechanical and thermal design of vaporizers account for frosting. An experimental set-up has been designed and effects of flow rate and ground clearance on the performance of ambient air vaporizers are evaluated. The flow rate is increased from the rated capacity of 500 Nm^3/h to 640 Nm^3/h and ground clearance is reduced from 500 mm to 175 mm. The above variations reduce the time duration for which gaseous nitrogen is delivered at temperature higher than 10.1°C (desired). Hence duty cycle reduces from eight hours to five hours. The other factors affecting performance such as fin configuration, fluid type, fluid pressure, intermittent flow nature and climatic conditions are assumed to be constant over the test duration. The decrement in outlet gas temperature (from 38 °C to 10.1°C) with corresponding increment in frost thickness leads to deterioration of performance of ambient air vaporizers.

1. Introduction

Ambient air vaporizers are vertically oriented, downdraft heat exchangers using ambient air as the source of energy to regasify cryogenic liquids. A schematic of downward draft generation is shown in ‘figure 1’. As shown in ‘figure 1’, the initial rows of fin surface exhibits higher frost

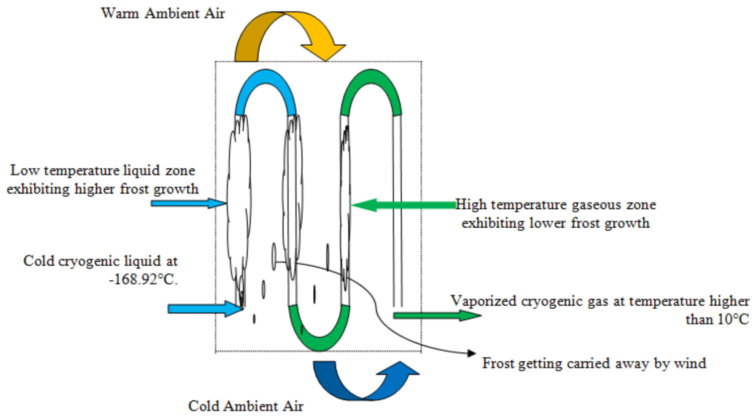

Figure 1. Schematic of downdraft generation in ambient air vaporizer.

accumulation than the final rows. This is due to fact that initial rows exhibit comparatively low surface temperature unlike final rows of vaporizer.

The vertical orientation of vaporizer creates a natural downdraft due to the warmer, less dense air at the top being lighter than the cold denser air at the bottom. The extremely lower surface temperature exhibited due to large temperature difference between ambient air and cryogenic liquid causes frosting on heat exchanger surface. Frosting induces additional load on equipment and reduces its heat transfer effectiveness thereby rendering them inefficient. This necessitates use of different defrosting mechanisms e.g. mechanical scrubbers, hot water spray on the surface, switching off the supply of liquid nitrogen to vaporizer. In present work switching off defrosting mechanism is used. The equipments are therefore rated for a specified duty cycle and require some defrosting time after each frosting cycle. But these heat exchangers are widely used due to inherent benefits that they offer in terms of ease of design, lower operating and constructional cost and lesser environmental impact in comparison to other vaporization systems.

The performance of ambient air vaporizers is a function of cumulative effect of different factors like fin configuration, fluid type and pressure, intermittent / steady flow nature, climatic conditions like temperature and humidity and ground clearance. Alteration of any parameter shall change the performance of equipment in terms of reduced flow rate being vaporized or in terms of reduced duty cycle for the rated flow rate. Hence, optimum selection of operating parameters is essential for efficient operation of vaporizers. Sizing ambient vaporizers for particular applications is generally done on thumb rule interpretations which involve multiplication or division of factors to the rated capacity. The factors used are mostly based on past experiences. For example, in northern parts of the USA and most of Canada, some companies use the quarter rule of thumb; divide the vaporizers rated capacity by four to obtain the actual mid-winter capacity. Others divide by 5, while in the southern states the rated capacity is multiplied by 1.5 for intermittent use and divided by 2 for continuous applications. While this rule of thumb method is generally satisfactory for different locations, applications and climates, it can be misleading for other locations because the multiplication or division of factors to the rated capacity is specific only to that user. Furthermore, it is based on the vaporizer manufacturers rated capacity, which is subject to question as configuration and safety factors may vary. Hence, it is better to adjudge performance by conducting experimental investigation on vaporizers.

Present research focuses on experimental set-up design and investigating effects of flow rate and ground clearance on the performance of ambient air vaporizers. Different parameters like pressure, temperature, flow rate and frost thickness are noted and analysed to assess the varying performance of ambient air vaporizers. Frost thickness is measured at different locations from start to end of vaporizer by using linear measuring tape strips. Its value at the end of duty cycle is found to be varying from 12 mm on the initial three rows, 5 to 7 mm on successive two rows and 0 mm on the end three rows. The frost accumulation results in cold gas outflow from the vaporizer.

2. Design of Experimental set-up

2.1. Vaporizer specification

A vaporizer to vaporize 500 Nm^3/h of liquid nitrogen at 10 bar operating pressure and temperature greater than 10°C is to be designed. Table 1 exhibits the configuration and dimensions of the fin are provided as input data for the sizing calculations. The fin material used is aluminium alloy.

Table 1. Given data or available data.

Tube inside diameter (m)	0.02505
Tube outside diameter (m)	0.03050
Liquid fins (m^2/m)	0.647
Gaseous fins (m^2/m)	1.345
Thickness of metal tube (m)	0.005

2.1.1. Estimation of sizing parameters for vaporizer. An average value of overall heat transfer coefficient U is to be determined for preliminary sizing. This is determined by theoretically accounting variation of inside heat transfer coefficient with varying vapour quality 'x' [2] [3] [4] [5] [6] and then taking a conservative value of inside heat transfer coefficient along with calculation of outside heat transfer coefficient by suitable correlation. The average value of overall heat transfer coefficient comes out to be 9.95 W/m^{2}K [6]. Applying basic heat balance equation as in equation (1), area required by vaporizer to deliver desired flow rate is determined. The mass flow rate $\dot{m}$ to be vaporized is 0.17 kg/s. This is calculated by converting volumetric flow rate to mass flow rate.

$$Q = \dot{m} \times \Delta H \tag{1}$$

$\dot{m}$ = mass flow rate, kg/s
ΔH=enthalpy difference between entering and leaving fluid, kJ/kg
Enthalpy difference is calculated by taking properties at operating pressure of 10 bar (a) and stated temperature conditions as shown in equation (2).

$$\Delta H = H_{outlet} - H_{inlet}, \text{ kJ/kg} \tag{2}$$

The mean temperature difference is calculated by using equation (3). This is done by evaluating temperature differences at inlet and outlet by using equations (4 and 5) respectively.

$$LMTD = \frac{\Delta T_i - \Delta T_o}{\ln\left(\frac{\Delta T_i}{\Delta T_o}\right)} \tag{3}$$

Where,

$$\Delta T_i = T_{ai} - T_i \tag{4}$$

T_{ai} = air temperature at inlet
T_i = fluid temperature at inlet

$$\Delta T_o = T_{ao} - T_o \tag{5}$$

T_{ao} = air temperature at outlet
T_o = fluid temperature at outlet
Now, area required to vaporize specified flow rate is calculated by using heat balance equation (6).

$$A_r = \frac{Q}{U \times LMTD} \tag{6}$$

Taking the star fin configuration's surface area (as specified by manufacturer) into account, length and number of finned tubes required to vaporize the rated flow rate of liquid nitrogen is estimated. The representative sketches of liquid and gaseous fin configurations are shown in 'figure 2a' and 'figure 2b'. The pressure is assumed to be remaining constant and this is validated by mathematical model [5].

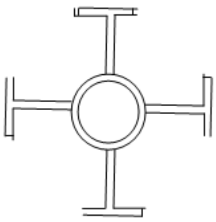

Figure 2a. Liquid fin configuration.

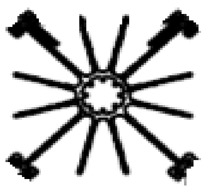

Figure 2b. Gaseous fin configuration.

As per the sound engineering industrial practice, 10% to 20% of the required area for vaporizer is provided with fins having less heat transfer surface area (i.e liquid fins) to accommodate frosting. The frosting occurs more at the initial length of the tubes due to high temperature difference available at the initial portion of the vaporizer. Also heat transfer rate is higher in the initial portion and hence it would be uneconomical to go for higher surface area fin in the initial portion of vaporizer. The symmetry of vaporizer also needs to be taken into account before finalizing the percentage of surface area to be occupied by each of liquid as well as gaseous fin type. Here, the initial 15% of the total area required i.e 100.31 m^2.for vaporizer is provided with liquid fins. Hence, area covered by liquid fins is $A_{rlf} = 0.15 \times 100.31 = 15.04\ m^2$. The initial fins taken are having a surface area of 0.647 m^2 per meter length of tube. Hence, total length of such fins is 23.25 m. The remaining area $A_{rgf} = 0.85 \times 100.31 = 85.26\ m^2$ is provided with gaseous fins having larger heat transfer surface area. These fins provide 1.345 m^2 surface areas per meter length. Hence, total length of gaseous fins is 75.91 m. Considering 15% safety margin for tolerance purpose, the lengths of liquid fins comes out to be $L_{lf} = 1.15 \times 23.25 = 26.73$ m and, length of gaseous fin $L_{gf} = 1.15 \times 63.39 = 72.89$ m .Each fin is having a length of 2.275 m prepared by extrusion process. Hence, $N_{flf} = 11.75$ and $N_{fgf} = 32.04$ number of liquid and gaseous fins respectively are required. The designed vaporizer is provided with 12 liquid fins and 36 gaseous fins. Thus, the symmetry of the vaporizer is also maintained. The symmetry does have an impact on mechanical calculation. The vaporizer tubes are connected to each other by U-bends.

For velocity of flow inside the tubes, sound engineering practices recommends liquid flow velocity to be between 2 to 5 m/s and gaseous flow velocity to be between 10 to 30 m/s. Hence, sizing of headers should be done such that the velocities are within allowable limits. Based on mass flow rate of cryogen passing through the tube and availability of standard header tubes, inlet header tube of diameter 19 mm and outlet header tube of diameter 40 mm is selected, as the diameter serves the criterion of velocity limits. The length of the inlet header tube is 1.11 m and outlet header tube is 1.15 m to accommodate six sub branches from the main inlet and outlet header lines.

2.1.2. Experimental set-up description. Experimentation is carried out to test the performance of Ambient Air Vaporizer in actual working environment. This is to ensure that the sizing method employed for the equipment satisfies the requirement or not and hence can be checked for its validity.

The liquid is withdrawn from the storage source having pressure higher than operating pressure of the vaporizer. The operating pressure for the vaporizer is kept constant at 10 bar (a) or 8.98 bar (g) with the help of pressure regulator installed on tank. As shown in 'figure 3' at the inlet of the test section AVC-500, a temperature gauge TE1 and a pressure gauge PG1 are installed. Various temperature sensors are installed at various intervals of length on finned tube surfaces to give surface temperature at various locations. Thereby average of all temperature readings determines the surface temperature. At the outlet of test section, a temperature gauge TE2 and a pressure gauge PG2 are installed. The difference of pressure gives pressure drop across the test section. A variable area flow meter is used to indicate the flow rate. Meanwhile we will also measure the frost growth on the finned surface at various intervals of time and at various locations on the finned surface and then take average of the thicknesses at various locations to indicate frost thickness.

2.1.3. Experimentation set-up process and instrumentation diagram.

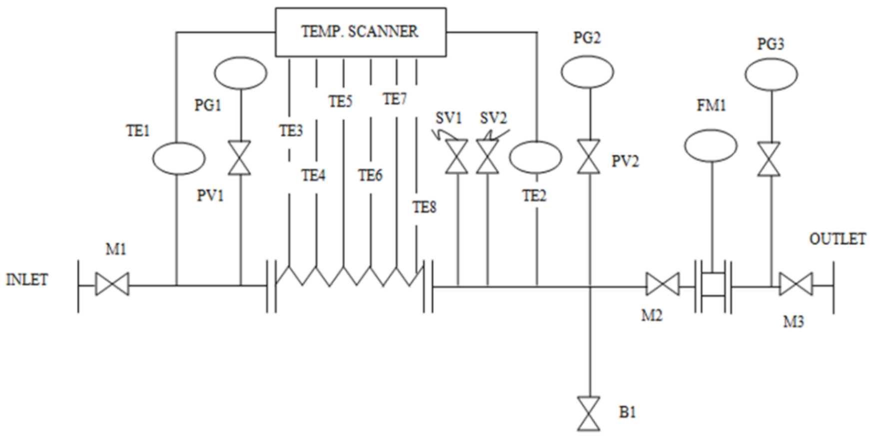

Figure 3. Process and instrumentation diagram of experimental set-up.

2.1.4. Technical specifications of flow components.

Table 2. Details of instrumentation used.

Tag No.	Size	Description
M1	25 NB	Long stem globe valve
M2, M3	40 NB	Long stem globe valve
SV1, SV2	½" NPT male	Safety valve
FM1	3" connections	Flow meter
B1, PV1, PV2, PV3	¼" NPT male	Isolation needle valve
PG1, PG2, PG3	¼" NPT ,100 mm Dial	Pressure gauge
TE3 to TE8	RTD PT-100	Plate type surface temperature element
TE1	RTD PT100, for 25 NB line	Temperature element with thermowell
TE2	RTD PT100, for 40 NB line	Temperature element with thermowell
Data logger	8 channel	Temperature Scanner

3. Experimentation procedure for performance evaluation

3.1. Brief outline of experimentation procedure for validation of sizing procedure and duty cycle

3.1.1. Experimentation procedure.

i. Fill required quantity of liquid in the tank keeping it undisturbed for test duration.
ii. Keep the PBU inlet and outlet valve **OPEN**. PBU is another vaporizer that vaporizes liquid nitrogen in required quantity thereby maintaining the desired constant pressure in the tank by setting the regulator on the PBU circuit.
iii. Select the test section on which experiment need to be carried out.
iv. Connect the liquid delivery line from the tank to the inlet of the vaporizer and connect the flow components as shown in the attached drawing for the experimentation set-up. The flow components shall be connected at least 1.5 m away from the outlet flange of the vaporizer. Keep all valves on the vaporizer circuit open and allow the gas vaporization to begin.
v. In the gas flow condition adjust the control valve in the outlet line of the vaporizer to get the desired vaporizer operating pressure in the gauge. Wait for pressure stabilization for 5 minutes, if required make fine adjustments.
vi. Record flow rate, pressures at inlet and outlet, inlet temperature of liquid nitrogen, outlet gas temperature, ambient temperature and surface temperature.
vii. Calculate the actual measured flow rate by applying correction factors for flow meter and conversion factors of temperature to arrive at flow rate of gas in Nm^3/h. Check the theoretical value of flow rate with the corrected value of flow rate.

3.1.2. Benchmark for flow rate and duty cycle validation.

i. The measured flow rate should be higher than the calculated flow rate.
ii. The temperature of the outlet gas should be at least 10 degree Celsius.

3.1.3. Factors whose effects are to be analysed during experimentation process. The vaporizer model on which testing is carried out are well endorsed for the performance under rated condition. The vaporizer gives rated flow of 500 Nm^3/h of gaseous nitrogen at desired outlet gas temperature of 10°C for rated duty cycle of eight hours. This is when vaporizer is mounted on the foundation having 500 mm height to ensure proper cold air flow and dense air mitigation from the bottom. To analyse the effect of above factors, vaporizer will be allowed to vaporize higher flow rate than its rated capacity with reduced ground clearance of 175 mm and then duty cycle shall be determined based on criteria mentioned above in section 3.1.2.

3.1.4. *Observation table*

Table 3. Temperatures of fluid inlet and outlet, ambient air, flow meter and fin surface reading.

Time intervals min.	Liquid inlet temperature, TE1 (°C)	Outlet gas temperature, TE2 (°C)	Ambient temperature, Ta (°C)	Temperature differences, (°C)		Flow rate at outlet FM1, Nm^3/h		Average fin surface temperature, $T_{s,avg}$ °C
				Inner fluid ΔT1 = TE2-TE1	ΔT 2 = Ta-TE2	Indicated	Actual	
0	-168.92	38	34	209.82	Absurd	500	599.22	24.686
30	-168.92	33.3	34	202.22	0.7	520	628	-11.13
60	-168.92	27.2	35	196.12	7.8	520	634.5	-38.36
90	-168.92	25.7	36	194.62	10.3	520	635.95	-48.93
120	-168.92	22.3	37	191.22	14.7	520	640	-60.47
150	-168.92	20.2	37	189.12	16.8	520	642	-66.01
180	-168.92	18.9	38	187.82	19.1	520	643	-68.73
210	-168.92	18.8	39	187.72	20.2	520	643	-69.325
240	-168.92	16.7	39	185.62	22.3	520	645.3	-72.59
270	-168.92	15.4	39	184.32	23.6	520	647.32	-72.74
300	-168.92	10.1	39	179.02	28.9	520	653.5	-75.75
330	-168.92	5.9	40	174.82	34.1	520	658	-78.41
350	-168.92	0	39	168.92	39	520	665.2	-80.81

4. Results and discussion

During theoretical analysis it was observed, the value of overall heat transfer coefficient does not change much with the change in vapor quality, although the change in vapor quality has a marked effect on the value of inside heat transfer coefficient of liquid nitrogen boiling inside the vaporizer tubes as shown in 'figure 4'. This clearly indicates that the variation in value of overall heat transfer coefficient used in the above calculation depends primarily on variation in value of outside heat transfer coefficient and not on the inside heat transfer coefficient value. Hence, assuming a conservative value of inside heat transfer coefficent, the variation of outside heat transfer is analysed. During analysis it is observed that an increase or decrease in the value of outside heat transfer coefficient has a marked effect on the overall heat transfer coefficient value. The value of heat duty offered and outside heat transfer coefficient reduces during ambient air vaporizer operation owing to decrement observed in outlet gas temperature. This in turn reduces value of overall heat transfer coefficient as shown in the 'table 4' below.

With reduced ground clearance of 175 mm, the time duration for which gaseous nitrogen is delivered at temperature higher than 10.1°C (desired) reduces from eight hours to five hours. The reduced ground clearance doesnot allow proper air flow from the bottom of vaporizer. This causes frost formation rate to increase as cold air gets accumulated at the bottom of vaporizer. Hence duty cycle reduces from eight hours to five hours. The value of frost accumulation at the end of duty cycle is found to be varying from 12 mm on the initial three rows, 5 to 7 mm on successive two rows and 0 mm on the end three rows. The row distribution is as mentioned in 'figure 5'. Even similar values of frost formation were found for 500 mm ground clearance case but the rate of frost accumulation was lower. The above values of frost formation were attained after a duty cycle of eight hours for 500 mm ground clearance case.

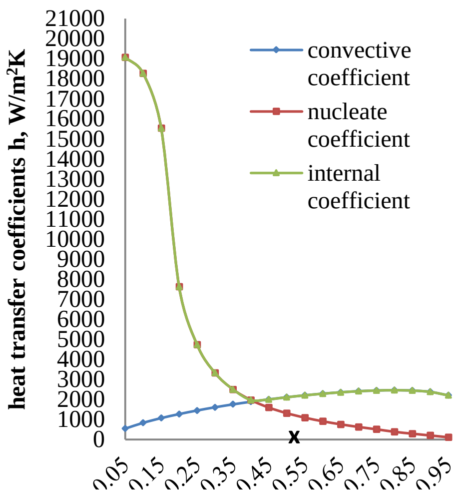

Figure 4. Variation of inside heat transfer coefficients with vapour quality.

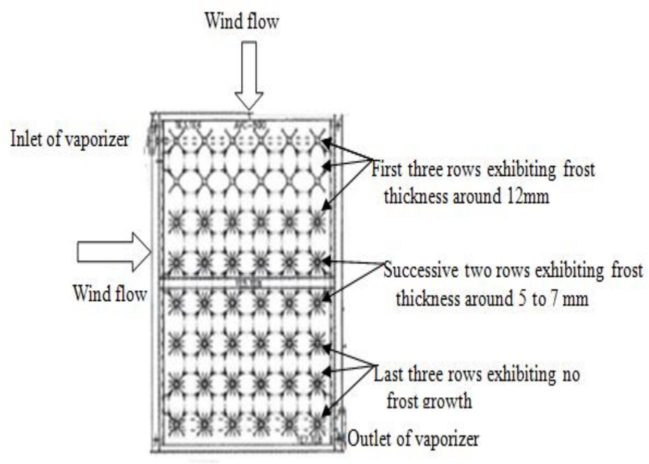

Figure 5. Configuration of test section with frost growth information.

Table 4. Variation of heat duty, LMTD, outside and overall heat transfer coefficient with time.

Time intervals min.	Heat transfer surface area, (m^2)	Heat duty, Q (W)	LMTD	Heat transfer coefficients, (W/m^2 K)		Overall heat transfer coefficient, U=Q/(A*LMTD) (W/m^2 K)	Overall heat transfer coefficient U (By theoretical equation)
				h_o outer	h_i inner		
0	127.82	66927.42	-	-	-	-	-
30	127.82	66060.68	35.66	11.45	2194.8	14.48	18.78
60	127.82	64949.04	60.09	6.92	2194.8	8.45	11.38
90	127.82	64671.13	65.07	5.95	2194.8	7.77	9.79
120	127.82	63976.35	72.44	5.13	2194.8	6.90	8.45
150	127.82	63628.96	75.46	4.83	2194.8	6.59	7.95
180	127.82	63437.9	78.82	4.65	2194.8	6.29	7.65
210	127.82	63403.16	80.51	4.57	2194.8	6.16	7.54
240	127.82	63021.03	83.14	4.41	2194.8	5.93	7.27
270	127.82	62800.4	84.70	4.39	2194.8	5.80	7.24
300	127.82	61791.27	90.72	4.21	2194.8	5.32	6.94
330	127.82	61023.55	96.44	4.03	2194.8	4.95	6.64
350	127.82	59951	100.93	3.91	2194.8	4.64	6.45

The decrement in outlet gas temperature is observed due to vaporizer becoming inefficient. This is due to increased frost growth with the passage of time which acts like an insulation in the heat transfer path thereby reducing heat transfer efficiency. Hence, ambient air vaporizers are rated for specified duty cycle and require defrosting after every cycle of operation.

5. Conclusion

From the performance test conducted on ambient air vaporizer effect of flow rate and ground clearance were analysed. Increasing flow rate from the rated capacity of 500 Nm^3/h to 640 Nm^3/h and reducing ground clearance from 500 mm to 175 mm reduced the time duration for which gaseous nitrogen is delivered at temperature higher than 10.1°C (desired outlet gas temperature). The increased flow rate causes frost formation rate to increase and reduced ground clearance causes cold air accumulation at the bottom of vaporizer. The cold air accumulation further contributes to increased rate of frost formation. Hence the duty cycle reduces from eight hours to five hours. This implies that, as the flow rate is increased beyond the rated capacity and the ground clearance is reduced the frost growth tends to increase more rapidly than at the rated flow and higher ground clearance. The indicated flow was observed to be constant during the entire operation of the vaporizer, but the outlet gas temperature was observed to fall down rapidly over a period of time due to frost growth on the vaporizer fin surface. The sizing method was found to be sufficient for the rated capacity of flow and operating conditions. Hence, the method can be adopted for sizing of ambient air vaporizer models.

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