live export

LIVE.211

Practical Ventilation Measures for Livestock Vessels

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Practical Ventilation Measures for Livestock Vessels

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Executive Summary

The following "dot points" summarise and form an index to the concepts explained in the report. While this report is a summary of practical measures noted during work for the Livestock Vessel Ventilation Report, the "dot points" below are still further distilled. As a result, caution is urged in interpreting this summary without also referring to the explanations available.

2. Practical Measures for New and Existing Ships

2.1 Ventilation Intakes
- 'Mushroom cap' intakes decrease flow, or cost power, or do both together.
- A little bit of inlet flaring helps a lot.

2.2 Ducts Bends and Elbows
- Avoid sharp duct elbows where possible.
- A little bit of corner smoothing helps a lot.

2.3 Duct Discharges
- Supply air outlets should be smooth, with no extraneous grilles or baffles.

2.4 Flow Balancing (Supply vs Exhaust)
- For closed holds, reversing exhaust fans to supply is likely to be counter-productive.

2.5 Flow Balancing (local outlets)
- Restrictions applied to balance the supply outlet flows should be the minimum practical.

2.6 Jetting of Air
- Supply air should be delivered in jets over the backs of animals in each pen.

2.7 Avoiding Dead Spots
- To avoid dead spots, air should be actively supplied (in jets) to all areas (preferably each pen).
- Local fans may also ensure the necessary air exchange through mixing if jetting is not possible.

2.8 Measuring Air Properties
- Shippers should ensure that the crew members are fully informed on the correct use of instruments to measure air properties.

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2.10 Wet Bulb Temperature
- Wet bulb temperature is the appropriate measure of the thermal environment for cattle on ships.
- Relative humidity is not useful except in calculating wet bulb temperature.

2.11 CO_2 As An Indicator
- CO_2 level gives a direct measure of the ventilation effectiveness at any location.
- CO_2 is also useful for identifying recirculation of exhaust air.

2.12 Cattle Wetting
- Wetting livestock so that water runs off the skin will remove body heat and give some respite.

2.13 Course Alteration

- In a following breeze, altering course by say 10 to 30 degrees can significantly improve open deck conditions with minimal increase in sailing time.
- Turning circles gives only temporary relief and is not worth doing.

2.14 Hot Bulkheads

- Hot surfaces (bulkheads, cover decks or tanks) can add significantly to the stress of nearby livestock.
- Animals should be shielded from hot surfaces by insulation or "double skinning" on the surfaces.

3. Practical Measures for New or Re-fitted Ships

3.1 Avoiding Recirculation

- Recirculation of exhaust air can be a serious problem.
- Recirculation has been observed to result in effective ventilation rates being halved.
- Exhaust should be directed forcefully away from the ship.
- Intake air should not be sourced alongside open decks or near exhausts.

3.2 Air Supply and Exhaust Locations

- It is beneficial to provide many supply air outlets closely spaced around the hold.
- Preferably each pen should have two or more supply jets directed at it.
- Exhaust may be collected at fewer, more central locations without detriment.

3.3 Cost Functions

- Much can be learnt about the economic trade-offs in ventilation design by a mathematical approach relating cost to the various parameters.

3.4 Noise

- Noise can be an issue for port neighbours, crew quarters and personnel working below decks.
- The first effort in minimising noise should be to minimise the total fan power.
- Industrial 'splitter' attenuators could control the noise but may be excessively bulk and clumsy to fit on board.
- Cylindrical 'jet fan' style attenuators appear to be a practical approach, offering a noise reduction of 8 to 12dB.

3.5 An Ideal Ship?

- The "ideal" ship will be different for each shipping business. The following "dot points" represent only one such solution.
- Subject still to the findings of the sheep ventilation project, forced ventilation with high sided ships is preferred to open decks.
- Below the weather (sea tight) deck, supply and exhaust ventilation would be balanced.
- Upper decks would be exhaust only, with intake through the (non-sea tight) sides.
- Supply air would be through multiple nozzles with exhaust in large, more central risers.

4. Air Flow Facts

4.1 Composition of the Atmosphere

- Dry air is almost four-fifths nitrogen and around one-fifth oxygen, with only around 1% made up of other gases.
- The most humid air carries only around 4% water vapour.

4.2 What is a Gas?

- Air is a chaotic mixture of widely spaces molecules.
- Although gas molecules can be 'squeezed' closer together to increase density, air can be treated as an incompressible but light liquid when calculating ship ventilation flows.

4.3 Air Flow Friction

- Ship ventilation flows are fully turbulent.
- Duct pressure drop is proportional to the square on the duct velocity.

4.4 Fan Power

- Fan power is proportional to the cube of the duct velocity.
- Small changes to the duct size will have much larger effects on fan power.

4.5 Humidity, Density, Pressure Change and Flow Resistance

- As in Section 4.2, changes in humidity, density and temperature of the air are small enough that they need not be considered in design of mechanical ventilation for livestock vessels.

4.6 Fans and Rain

- There should be no harm to the fans by eliminating intake caps and allowing rain to enter intakes freely.

1. Introduction

A major study into ventilation efficacy on livestock export vessels was completed in July 2001. Following that study, there was a need for a more succinct report focussing on practical measures, which could be implemented by exporters and shipowners to improve ventilation or reduce costs. This brief report on operational measures or modifications seeks to fill that need.

This report is principally a documentation of ideas generated by the MAMIC project team during and after the previous ventilation study. It gives a few paragraphs on each suggested measure, accompanied by diagrams as required. While some explanation is given of the reasoning behind each measure, it does not include the level of scientific justification normally seen in a research report. The emphasis is on accessibility of the thoughts to the industry generally.

The focus of the earlier work, and of this report, is on the hot conditions experienced in transit to the Middle East. Ventilation effects in cold climates are not addressed.

The suggested practical measures are divided into two sections with the first applicable to both new and existing ships and the second only relevant where new design or re-fitting gives scope for greater change.

The report also includes a section on basic facts of ventilation aimed at providing operators with an enhanced level of understanding of ventilation systems and dispelling some of the 'myths' heard occasionally through contact with those employed in the industry.

This report is informative in nature, being intended for ship owners, senior ship crew and exporters. It has not been framed to alter standards or regulations.

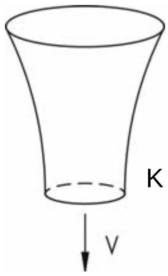
2. Practical Measures for New and Existing Ships

2.1 Ventilation Intakes

Ventilation intakes affect the ventilation outcomes in two ways. Firstly they create a pressure drop, decreasing flow or requiring higher fan pressure. Secondly, and often more critically, they determine the evenness of flow into the supply fan, which is generally close to the inlet. Poor design of ventilation intakes was observed to be common across most of the live export fleet. Intake covers, variously resembling 'mushroom caps' or 'chinaman's hats' as sketched below appear almost universally. They are generally not generous in proportion and are often located only a short distance above the fan. The table of pressure loss factors for the mushroom cap illustrated demonstrates how large the associated pressure drop can be. The figures give approximate pressure loss coefficients 'K'. Very approximately, for a 1m duct, a K value of 1.0 gives a pressure loss equivalent to that of a straight duct run of 40 to 50m.

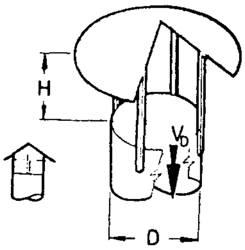
The effect on fan performance can be even more significant than the intake pressure drop. Fans are designed to operate with uniform, parallel flow upstream of the blades. If this is not the case, the fan blades may under-perform or even stall. Obviously this decreases flow below the fan's potential and results in higher power consumption for a given flow. There is little point dwelling on exactly how damaging they are; it is far easier to make sure they have no place on a ship. The effect of the ingress of rain, which will occur without intake covers, is discussed in Section 4.5.

That is; intakes on the current fleet were generally causing unnecessarily high pressure drops and frequently had characteristics expected to degrade fan performance.



K = 0.03

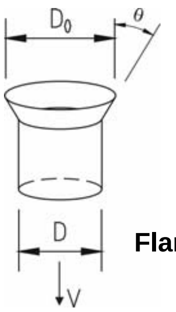
Bell Mouth Entry



$\frac{H}{D}$	0.2	0.4	0.6	0.8	1.0	∞
K	1.8	1.4	1.2	1.1	1.1	1.0

'Mushroom' Cap

The ideal intake is the 'bell mouth' intake sketched above however the proportions are somewhat impractical. Most of the smoothing effect can be achieved by a simple 300 to 450 flare extending out only a little larger than the duct diameter as per the sketch below. Preferably the intake should be at least 2 duct diameters from the fan.



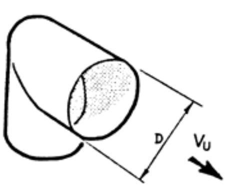
K		Inlet Diameter (D_0)	
		1.1D	**1.2D**
Angle (θ)	30^0	0.25	0.17
	45^0	0.32	0.23

Flared Duct Entry

2.2 Duct Bends and Elbows

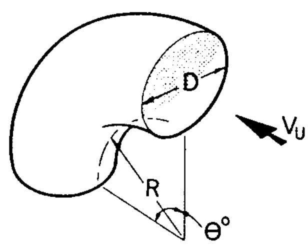
After intakes, the largest causes of pressure loss in the ventilation system are the bends, elbows and tees.

The sketches below show the pressure losses for a sharp elbow and the more ideal gradual bend. While the difference in pressure loss is very large, the sweeping bends are generally impractical except perhaps above the top cover deck.



K = 1.2

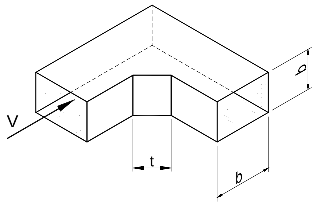
Sharp Elbow



RADIUS RATIO R/D	K
0.25	0.45
0.50	0.34
1.0	0.24
1.5	0.23
2.5	0.22

Gradual Elbow

As with the intakes in Section 2.1, pressure loss figures for the gradual elbow show that much of the pressure loss can be avoided with a moderate radius or chamfering of the corners. This is also demonstrated by the figures below for a square elbow with a chamfered inside corner.

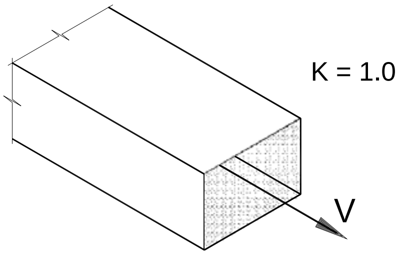


K	0	0.1	0.2	0.3	0.4	0.5
$\frac{t}{b}$	1.2	1.1	0.92	0.78	0.68	0.61

Chamfered Square Elbow

2.3 Duct Discharges

The discharge points from the end of a duct will always have the same pressure loss (K = 1.0). The kinetic energy of the flowing air is dissipated by turbulent mixing in the ventilated space. It is possible to recover some of this energy (and hence pressure) with a gradual expansion, however a jetting velocity over the livestock is highly desirable. The difficulty of installing gradual expansions, combined with the desirability of jetting, means that practically all supply outlets should be plain nozzles or holes. Nozzles are preferable in some situations as they give better control over the direction of the jet.



Exit

The discharge pressure loss through a hole in the side of a duct will depend strongly on the local duct geometry. A number of vessels had significant restrictions across outlets, presumably intended for balancing purposes (See Section 2.5). If these are overdone (e.g. applied to all outlets), then the overall fan pressure will have been unnecessarily increased.

Discharge outlets of exhaust ducts above the decks should preferably have gradual area expansions to increase efficiency. The size involves trade-offs in design and between capital and operating costs.

2.4 Flow Balancing (Supply vs Exhaust)

On many ships, the same flow capacity is provided for supply and exhaust so that the fans operate as intended with all hatches and accessways closed. If, during fair weather, it is possible to sail with hatches and accessways open, the overall ventilation flows may be increased by reversing some exhaust fans to operate as supply fans and allowing the openings to be unpowered exhausts.

There are a number of phenomena, which limit the applicability of this approach. For essentially closed holds, it is likely to be counterproductive. Because of the variability of fan and duct design and hold openings, it is not possible to make a general statement covering all ships. While the calculations need to be worked through for ships individually, the factors to be considered are common and are listed below.

2.4.1 Unidirectional Fans

The vast majority of fans in general industry and on ships are ‘unidirectional’. That is; their blades are designed for flow in one direction only. The leading edges are round, the trailing edges sharper and the blades have a curve or ‘camber’ from leading to trailing edge, a little like the curve in the sails of a dinghy. When these fans are reversed, the leading edge is too sharp, the trailing edge is too blunt and the camber is in the wrong direction. Consequently, they typically operate in reverse at less than half their efficiency in the forward direction. If the forward operation has been compromised by bad inlets (see Section 2.1), then the deterioration in reverse operation may not be so apparent.

'Reversible' or 'bi-directional' fans are manufactured for particular applications. Their blades have no camber, and have sharpish 'leading' edges on both edges. They sacrifice a little efficiency in the forward direction to achieve the same efficiency in reverse. They are common as jet fans in road tunnels where reversibility is generally a design requirement (as an assembly with sound attenuators on both ends, they can be seen hanging in the Harbour Tunnel, Eastern Distributor and M5 East Motorway in Sydney, CityLink in Melbourne and the Northbridge Tunnel on the Graham Farmer Freeway in Perth).

Clearly, if the exhaust fans are unidirectional, when they are operated in reverse, they will not be as effective as a dedicated supply fan.

2.4.2 Restrictive Openings (Closed Holds)

If the openings intended to operate as exhaust routes are restrictive then the 'backpressure' on the supply fans will be higher than designed. This may act to reduce the flow produced by the supply fans, particularly for those which are exhaust fans reversed to operate as supply fans.

Obviously, if there are no openings other than fan ducts, then the higher deck pressure will increase the flow through each exhaust fan and decrease the flow through each supply fan. It is doubtful that any benefit can be achieved in this case, other than a local relief for the pens next to the new supply outlets. Other areas may in fact see less flow. To take the approach to its logical extreme, it is obvious that if all fans were identical and all on 'supply mode' there would be no flow at all into the decks.

If the openings are primarily accessways, then the pressure below decks will be evidenced by the flow velocity through the openings. On a number of ships, the flow velocity through accessways was very high (in excess of 10, and up to 15m/s). This can create a dust hazard for personnel and should be avoided.

2.4.3 Disposing of Exhaust

Exhaust fans typically throw the contaminated air vertically at high speed above the top cover deck. With relatively open decks, as exhaust fans are turned to supply, more of the exhaust leaves the decks at low speed. Any exhaust dribbling from hatches or open sides can form a cloud around the ship and is more likely to be recirculated below decks, effectively reducing air turnover rates (see Section 3.1).

2.5 Flow Balancing (local outlets)

This is one issue in livestock ship ventilation which is the same as in office buildings. In office buildings, the supply outlets are called registers or diffusers. The task is to balance the supply air flow to the heat load of each room or space. The pressure in the room or space is essentially atmospheric and so the only adjustment is by changing the resistance of the ducts and registers. Office buildings generally have balancing dampers (valves) to change the relative resistance of duct branches. Adjustment may also be made by adding restriction at or near a particular register. In balancing the flows, the resistance of the total system is increased. While this is a slight energy cost for an office building, it is more significant on ships as it not only represents a significant running cost but also increases the required generator capacity.

Ideally, the only pressure loss through the register should be the pressure necessarily 'thrown away' to create the jet of supply air. Any adjustment to flow should then be done by restricting the outlet area. On several vessels, we saw outlets which absorbed a significant fraction of the fan pressure for no material gain in jetting or otherwise.

The primary flow balancing is obviously done at the design stage, with careful consideration of the duct losses to each register. On commissioning, all registers are initially left as open as possible, with iterative adjustment downwards until the required balance is achieved. Note that the register flows all interact with each other through the duct losses and the fan curve. There are many air conditioning consultants and contractors able to carry out this type of balancing however the less able of them may have trouble, as ships will have higher pressures and velocities and unusual registers when compared to office buildings.

2.6 Jetting of Air

Introducing the supply air as jets with significant velocity (above say 8m/s) has two beneficial effects.

Air moving over the skin of livestock increases the rate of heat transfer from the skin to the air. That is; in hot conditions, a breeze improves physiological comfort. This is self-evident to anyone living in a tropical climate. It can be very significant to livestock on the verge of heat stress. An airspeed as low as 0.5m/s can be a significant help, allowing the skin to be several degrees cooler for the same metabolic heat rejection. A supply air jet of reasonable flowrate, jetting at 10m/s can spread to give 0.5m/s or more over a significant fraction of a pen. The beneficial effects of airspeed are known theoretically and have been observed practically on ships. It is strongly recommended that supply air be directed through nozzles over the animals in every pen. Preferably two jets should be provided per pen.

The second effect of jetting is to assist in avoiding the creation of dead spots which can occur if the design relies on the supply air drifting evenly along the deck (see Section 2.5).

2.7 Avoiding Dead Spots

Pen areas through which the net fresh air flow is well below the deck average will obviously be hotter and smellier than other areas. Such ‘dead spots’ can be in the same areas each voyage but can also reportedly relocate across the ship or to a different part of the deck.

An understanding of the flow driving forces helps in understanding the ‘movement’ of dead spots and also the methods for eliminating them.

Areas of some decks on some ships are supplied with fresh air using large but infrequent risers. The remoteness of the supply vents means that the introduced air drifts very slowly along the deck in some areas. A slow drift in this way will never be uniform as it is subject to modification by the tiniest of influences. Minor temperature differences around the deck could be sufficient for this. For example, a circulation velocity of 0.1m/s (high for a drift velocity) could be driven by one area of the deck being less than 0.1^0C hotter than other parts. As the temperature rise between inlet and exhaust is of the order of 2 or 3^0C, temperature variations around the deck of 0.1^0C or more are a certainty.

The livestock are the largest source of heat and so, as the animals move in the pen to feed or lie down, the location of the heat source changes and the drift of the air may be altered. From voyage to voyage, changes to pen loading could affect the drift patterns. The warmth of the sun on the ship sides may even be sufficient to drive flows.

Given that the drift patterns are so uncertain and are likely to create dead spots somewhere, it is clear that a general drift is not a reliable way to supply fresh air to all pens.

The best solution is to provide jetting of air, as described in Section 2.6, into all pens. This not only provides local fresh air, it also importantly ensures mixing across the deck and dominates the weak influences which might otherwise determine dead spot locations.

If jetting is not possible, a less ideal alternative is to provide the stirring and forced mixing using local fans. While local fans may ensure mixing, they obviously don’t offer all the benefits of a fresh local jet.

2.8 Measuring Air Properties

All instruments need a 'stabilisation time' to adjust to the environment being sensed. It is important to remove covers, turn-on and otherwise prepare the instrument in plenty of time and to make sure that the reading has stabilised in the environment before conditions are recorded.

2.8.1 Dry Bulb Temperature

'Dry bulb' or conventional temperature can be measured with simple mercury or alcohol-in-glass thermometers. There is a range of digital thermometers available and many anemometers and other instruments also sense and report temperature.

If there are warm bulkheads, strong lamps or other sources of radiated heat, it may be necessary to shield thermometers from the radiation (but not from the airstream).

2.8.2 Wet Bulb Temperature

The traditional method for measuring wet bulb temperature is using a glass thermometer with a wick to keep the bulb wet (actually just damp). These can be purchased paired with a second thermometer so as to give wet and dry bulb thermometers in one unit. It is very important that these be well ventilated. The stabilisation time can be significant. As a wet/dry bulb pair, they are also available in a unit known as a sling psychrometer. These resemble a 'clacker' used by football fans and are twirled around the handle in order to ensure good (forced) ventilation past the damp wick.

A number of digital 'thermohygrometers' are available to record wet bulb temperature. They actually measure humidity and dry bulb temperature and perform an internal calculation to give wet bulb temperature. Instruments which do not make the calculation can also be useful, as wet bulb temperature can be found from dry bulb temperature and humidity using standard charts or tables.

2.9 Pen Air Turnover

Pen air turnover, or PAT, is the preferred measure of ventilation rate. It is the ratio of the ventilation flow (typically in m^3/hr or m^3/s) to the pen area in the ventilated section (in m^2). PAT has the dimensions of a velocity and can be most conveniently written in metres per hour (m/hr).

To relate PAT to the dimensions of the livestock housing, it may also be explained as follows: If the fresh air could be introduced evenly through the floor of each pen and be extracted evenly through the ceiling above each pen, then the vertical air velocity through the floor and ceiling would be the PAT.

Because of the relationship between beast weight and stocking density and between liveweight and the production of heat and CO_2, PAT is a direct measure of the average effectiveness in controlling heat and pollutant build-up. On vessels monitored for the 2001 ventilation study report, PAT fell in the range of 100 to 300m/hr.

The traditional measure 'air changes per hour' relates flow to deck volume. With the same stocking density and heat load, a space with twice the deck height requires twice the flow to have the same 'air changes'. This treatment of deck height is the principal reason why 'air changes per hour' is not as relevant as PAT.

2.10 Wet Bulb Temperature

The temperature quoted on the weather reports is the 'dry bulb temperature', meaning that the bulb of the thermometer is dry when the reading is taken. If a damp wick is placed over the thermometer bulb, the reading will change to be the wet bulb temperature. The wet bulb temperature is always less than the dry bulb temperature. With very humid air, the wet and dry bulb temperatures will be similar.

Wet bulb temperature is the preferred index of environmental conditions for livestock. It indicates the potential for bodily cooling when conditions get very hot. Without internal body heat, a damp (sweaty) hide would approach the wet bulb temperature. If the wet bulb temperature is well below body core temperature, the animal cools readily. As the wet bulb temperature rises towards the body core temperature, cooling potential decreases and animals compensate by increasing blood flow to the skin, lungs and airways. Mammals can only survive for a short time if the wet bulb temperature reaches the core body temperature.

As hinted above, wet bulb temperature, relative humidity, absolute humidity and dry bulb temperature are inter-related. Absolute humidity is the moisture content (as a mass-ratio) in the air. It may be a relevant index in extreme conditions. Relative humidity is the ratio of the moisture content to the maximum moisture content possible at that dry bulb temperature. Relative humidity is not a useful measure in the context of animal heat stress.

2.11 CO_2 as an Indicator

With the many uncertainties of actual fan performance, supply air balancing, short-circuiting, recirculation, etc. it is nice to have a technique for measuring the real ventilation performance at any location. Measurement of the carbon dioxide (CO_2) level gives the ventilation outcome directly, however it is only applicable when the vessel is loaded (empty pens don't generate CO_2).

The technique works for the following reasons. Across all livestock (and indeed people), the rate of generation of both metabolic heat and CO_2, when resting, is roughly proportional to body mass. The rise of temperature (and general pollutants) below decks is therefore closely related to the rise in CO_2 level. Because of the issue of re-circulation, temperature rise is difficult to apply as a measure of ventilation (it is harder to be sure about ambient temperature and other heat sources). On the other hand, the ambient CO_2 level is well known (0.03%) and there are no significant CO_2 sources other than the livestock. The build-up of CO_2 indicates directly the build-up of pollutants generally, and heat in particular.

For cattle, the AMSA MO43 stocking levels result in the liveweight being almost proportional to pen area (it is not so for sheep). Hence, for cattle, the production of heat and CO_2 is approximately proportional to pen area. A measurement of CO_2 level then gives a direct indication of the real effective ventilation rate.

Assuming AMSA stocking densities and *Bos indicus* cattle generating heat at 2W/kg liveweight, a CO_2 level increase of 0.05% (above ambient level of 0.03%) indicates an effective pen air turnover (PAT) of around 300m/hr. From this known point, other CO_2 levels can be converted to approximate PAT figures by knowing that the PAT is inversely proportional to the rise in CO_2 level above ambient.

Because of the relationship between CO_2 level and the "freshness" of air, CO_2 is also very useful in identifying recirculation of exhaust air into the air intakes.

2.12 Cattle Wetting

Water has a thermal capacity around 1000 times that of air. That is; compared to air at the same temperature, water running over a hot surface (skin) can remove heat from the skin so fast that the comparable heat removed by the air is insignificant. The difference could be experienced by standing in swimming togs in a breeze at 20^0C and then diving into a swimming pool at 20^0C.

The heat removal characteristics of splashing water points to wetting cattle as a practice to reduce heat stress.

Observations were made during hot voyages of the 'comfort' of cattle around the time of washdown. It was found that the respiratory rates fell during washdown and stayed lower for a considerable period afterwards even through the deck environment returned rapidly to the pre-washdown conditions. It is suggested that the splashing of cattle removed sufficient body heat for the cattle to be comfortable for some time without panting. We believe there is scope for offering respite to stressed cattle on ships using sprinklers or even hand held hoses with nozzles.

The technique obviously depends on supply of fresh water which is cooler than the skin of the stressed cattle. Fresh water is preferable, however sea water will work just as well thermally.

Other practical considerations include the spoilage of fodder by the water sprays and arranging the activity to avoid alarming the cattle and causing further stress. The first of these makes it difficult to spray whole pens, while the latter makes hand held nozzles more problematic. Conditions underfoot may also become too sloppy with spraying, requiring a full washdown to be instigated.

2.13 Course Alteration

Ventilation of closed decks must always be by mechanical means, and with no doors being opened or closed or grilles blocked, the air flow won't change.

Ventilation of open decks with no forced ventilation is not so predictable. When the wind blows strongly past the ship, air exchanges will be high. With a following breeze, or still air when in port, the ventilation can be very poor.

The following course alteration protocol is appropriate for following breezes. By making slight deviations off-course (up to 30^0), significant apparent cross winds can be generated with only a minor slowdown in effective progress. The deviations could last from 10 minutes to a day or more as required, with the ship zig-zagging around the intended course. The new apparent wind speed and effective progress reduction can be readily calculated using trigonometry. The algebra can also be turned into a spreadsheet to give a ready reference management tool for use by ship's captains in making course alteration decisions given the breeze requirements of particular open decks, the weather, and schedule constraints.

The following table gives the results of a course alteration made when the relative breeze is exactly zero. That is; when the wind is blowing in the same direction as the ship is sailing, and at the same speed, the table gives the new relative wind that can be achieved for each ship speed and angle of turn. The table also gives the delay factor by which the sailing time would be increased if the course alteration was repeated cyclically. Lastly, the table gives the apparent direction of the new relative breeze. An apparent direction of 90^0 represents a cross-breeze through the pens from abeam of the ship.

Table of new apparent wind speeds (in m/s) for various ship speeds and turn angles, given zero relative wind initially

Angle of Turn (degrees)	Delay Factor	SHIP SPEED (KNOTS)								Apparent Wind Direction
		10	12	14	16	18	20	22	24	
0	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
5	1.004	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	87.5
10	1.015	0.9	1.1	1.3	1.4	1.6	1.8	2.0	2.1	85.0
15	1.035	1.3	1.6	1.9	2.1	2.4	2.7	3.0	3.2	82.5
20	1.064	1.8	2.1	2.5	2.9	3.2	3.6	3.9	4.3	80.0
25	1.103	2.2	2.7	3.1	3.6	4.0	4.4	4.9	5.3	77.5
30	1.155	2.7	3.2	3.7	4.3	4.8	5.3	5.9	6.4	75.0
45	1.414	3.9	4.7	5.5	6.3	7.1	7.9	8.7	9.4	67.5

For those wishing for a more detailed table, it is possible to construct a table covering all possibilities of relative wind direction before the turn is made. Such a table can only be for one combination of ship speed and turn angle. Separate tables are required for different ship speeds and turn angles. An example of such a table is given below. For most practical cases, the relative wind will be close to zero when course alteration is considered and so the table above will give sufficient guidance.

When an original course is resumed, conditions rapidly return to what they would have been had no course alternation been made. For this reason, short term diversions such as turning in circles only gives relief while the diversion is underway. Effective progress while turning a full circle is obviously zero and so sailing time is increased. Thus radical course departures do not assist overall animal comfort on the voyage and cannot be recommended.

Sample Course Alteration Spreadsheet for Management of Open Decks in Following Breezes

Speed of ship	**18** knots	9.26 m/s	1 nautical mile =	1850 m
Angle of turn (to s'board)	**30** degrees	0.524 radians	1 knot =	0.514 m/s
Delay factor (1 = no delay)	1.155			
Vs*(1-cosALPHA)	1.241	(Vs is ship speed in m/s ; ALPHA is the turn angle)		
Vs*sin(ALPHA)	4.63			

TABLE OF NEW APPARENT WIND STRENGTH AFTER A TURN (m/s)

Apparent wind direction before turn (starboard of bow)	Apparent wind speed (m/s) before turn											
	m/s	0	1	2	3	4	5	6	7	8	9.26	10
degrees	knots	0	1.946	3.892	5.838	7.784	9.73	11.68	13.62	15.57	18.02	19.46
0		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9
30		4.8	5.1	5.7	6.3	7.0	7.8	8.6	9.5	10.3	11.5	12.2
60		4.8	5.5	6.4	7.2	8.1	9.0	10.0	10.9	11.9	13.1	13.8
90		4.8	5.8	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.9	14.7
120		4.8	5.8	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.9	14.7
150		4.8	5.5	6.4	7.2	8.1	9.0	10.0	10.9	11.9	13.1	13.8
180		4.8	5.1	5.7	6.3	7.0	7.8	8.6	9.5	10.3	11.5	12.2
210		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9
240		4.8	4.1	3.7	3.4	3.4	3.8	4.3	5.0	5.7	6.8	7.4
270		4.8	3.8	2.9	2.0	1.4	1.3	1.8	2.7	3.6	4.8	5.5
300		4.8	3.8	2.9	2.0	1.4	1.3	1.8	2.7	3.6	4.8	5.5
330		4.8	4.1	3.7	3.4	3.4	3.8	4.3	5.0	5.7	6.8	7.4
360		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9

TABLE OF NEW APPARENT WIND DIRECTION AFTER A TURN (degrees starboard of bow)

Apparent wind direction before turn (starboard of bow)	Apparent wind speed (m/s) before turn											
	m/s	0	1	2	3	4	5	6	7	8	9.26	10
degrees	knots	0	1.946	3.892	5.838	7.784	9.73	11.68	13.62	15.57	18.02	19.46
0		75	63	51	39	29	21	14	9	4	360	358
30		75	64	55	48	41	37	33	29	27	24	22
60		75	68	62	58	55	52	50	48	47	45	44
90		75	72	71	69	68	67	67	66	66	65	65
120		75	78	79	81	82	83	83	84	84	85	85
150		75	82	88	92	95	98	100	102	103	105	106
180		75	86	95	102	109	113	117	121	123	126	128
210		75	87	99	111	121	129	136	141	146	150	152
240		75	85	98	113	130	145	158	167	174	180	183
270		75	79	85	97	123	167	198	212	220	225	227
300		75	71	65	53	27	343	312	298	290	285	283
330		75	65	52	37	20	5	352	343	336	330	327
360		75	63	51	39	29	21	14	9	4	360	358

2.14 Hot Bulkheads

The temperature of walls, ceilings and floors around the livestock is normally very close to the air temperature. A small amount of heat is radiated away from the animal's skin and an even smaller amount is radiated back from the walls, ceilings and floors. If a surface is significantly hotter than the air temperature then an extra heat load is placed on nearby animals. Those animals must dissipate their own body heat plus the radiated heat striking their skin. Because the balance of heat rejection is so fine when animals are stressed, relatively small levels of radiated heat can make a big difference.

Hot engine room bulkheads are most often mentioned in discussions on radiated heat. In terms of the number of animals affected, top cover decks are often far more significant than engine room bulkheads. Fuel oil tanks have also been observed as a source of radiated heat, after the fuel was heated to assist transfer. It is also likely that radiation from ships' sides subject to strong direct sunlight would affect animals along that side of the ship.

All normal ventilation approaches (jetting, increased PAT, etc.) will assist those animals subjected to higher thermal radiation. However, the best approach is obviously to stop the radiation at its source. This can be done by applying insulation material (slabs, blankets or foil) to either side of the hot surface. A second approach which is often more robust in the marine environment is to 'double skin' or duplicate a wall or ceiling with a ventilated air gap between the two skins.

Radiation is one of the reasons why reducing stocking density may assist livestock. Adjacent animals radiate heat at slightly higher rates than do the ship's surfaces. With less space between animals, the total radiation load from all surrounding surfaces (other animals and the ship) will be higher.

3. Practical Measures for New or Re-fitted Ships

3.1 Avoiding Recirculation

One of the simplest ways in which vessel ventilation efforts can be wasted is by the re-ingestion of exhaust air. If the air exhausting from a ship mixes with the air being drawn into intakes then obviously the intake air is not entirely fresh. If the intake air is 50% exhaust then the effective pen air turnover (Section 2.9) is only half what is was intended to be. As a result, CO_2 and ammonia levels, and the rise in wet bulb temperature, would all be twice what was expected.

Recirculation is increased when exhaust air is allowed to drift out of the decks and move as a cloud over the ship with the prevailing breeze. In this case, if the intakes are low on the top deck, or even worse, beside the upper decks, then they are likely to see a high concentration of exhaust air.

The solution is to use exhaust fans to throw the exhaust upward above the top deck so that any exhaust reaching the inlets is very dilute. Care should also be taken in locating inlets to avoid exhaust streams.

3.2 Air Supply and Exhaust Locations

Because of the ducting cost, and often also space constraints, there has been a reluctance to subdivide the supply and exhaust streams finely around the hold. Because of the benefits of jetting (see Section 2.5) and to avoid dead spots (see Section 2.6), it is recommended that the supply air be distributed around the hold. Preferably every pen should have one or two outlets directed at it. The distribution can obviously be done with multiple risers, by ducting on each deck, or by a combination of both.

The same arguments do not hold true for exhaust points. Whereas a supply outlet extends its zone of influence widely, through the spread and 'throw' of the issuing jet, an exhaust point has a tiny zone of influence. Thus the direction of air flowing into the exhaust points will not be determined by the precise exhaust location so much as the flow patterns generated by the supply outlets and thermal currents. The next question is whether it is necessary to locate exhaust risers as frequently as supply risers to prevent exhaust drifting across several pens. The reason is subtle, but the answer is no.

The reason lies in the level of contamination of the airstream. Consider part of a hold, 10 pens long with an exhaust at one end and identical supply to each pen. The pens are all equal in size and are stocked with the same liveweight. The air flowing past the last beast in pen 1 flows at the supply rate for one pen and carries the pollutants generated by the stock one pen. The air flowing past the last beast in pen 5 flows at the supply rate for 5 pens and carries the pollutants generated by the stock in 5 pens. Thus, on average, the concentration of pollutants past the last beast in pen 5 is the same as that past the last beast in pen 1. Similarly, the last beast in pen 10 feels the same concentrations, with pollutants from 10 pens being carried by the flowrate supplying all 10 pens. This argument can be extended mathematically to irregular pens and supply rates with the same conclusion; provided the supply air is well distributed and in proportion to pen area (or liveweight), the exhaust location does not affect the freshness of the local air. All pens will have the same average downstream exit conditions and all beasts will have access to fresh air supply jets.

If the supply air is delivered in well distributed jets as recommended then the air will be mixed vertically and the height of the exhaust points will not be significant. If the supply points are widely separated and ventilation is by a slow drift along the deck, it may be a slight advantage to locate the exhaust grilles up near the ceiling.

3.3 Cost Functions

The term ‘cost function’ means a mathematical expression relating the cost of a feature to its size, weight, power or other physical characteristics. For example, a cost function for ventilation duct would express not only how the fabrication cost varies with duct size but also the value of the deck space used up by ducts and the capitalised operating cost due to the duct resistance.

Livestock shipping operators stay profitable by minimising costs, so this section does not preach that message. Neither does it seek to detail how cost functions should be built up, as they will be different in each instance. Other industries use cost functions as a matter of course to minimise overall costs (or maximise value) at preliminary design stage. The point made here is that there appears to be scope in the design of livestock vessels for greater use to be made of a formal mathematical approach to cost minimisation. At the very least, the approach can be enlightening as to what considerations really are important to the bottom line.

3.4 Noise

Noise is thought not to be an issue for the livestock, however fan noise makes life less comfortable for stockmen below decks, may impact on crew quarters and can affect port neighbours when loading or discharging.

While there will be noise generated to varying degrees by air movement through ductwork, the primary noise source is the fans. Different fan models give slightly different sound power levels and with slightly varying frequency content, however the overriding consideration in reducing the noise at source is to reduce the fan pressure and hence the fan power. For a given flow, halving the pressure will reduce the noise by approximately 6dB. Reducing the pressure is a matter of duct and intake design (see Sections 2.1 and 2.2). Section 2.1 explains that poorly designed intakes can decrease fan performance. For the same reasons of flow non-uniformity, those intakes can also increase fan noise generation.

Once a fan is selected (or installed), there is still opportunity to attenuate the noise in ductwork adjacent to the fan. One way of minimising the noise to neighbours is to draw the intake air through industrial ‘splitter’ attenuators. These are large steel duct sections fitted with flow splitters made from perforated steel with sound absorbent filling. The sound is attenuated as it reflects from the porous walls of the narrow flow slots. While these attenuators can be very effective (say up to 30dB reduction), they are also rather large, with a cross-sectional area 2 to 4 times the fan area.

As a simpler alternative, we suggest the cylindrical attenuators as applied to the road tunnel jet fans mentioned in Section 2.4.1. These attenuators are a circular duct extension of the fan casing, enlarged to make room for a perforated, absorbent lining similar to that used in the industrial attenuators. As they provide a duct extension on the inlet side, these attenuators would also assist in ensuring a uniform flow into the fan blades, preventing the generation of additional noise as mentioned above. While not as effective as a splitter attenuator, the cylindrical attenuators could still be very beneficial and would be much cheaper and easier to fit onto a ship. The length of cylindrical attenuators is normally given as the ratio of the length to the fan diameter. That is; ‘1D’ or ‘2D’ in length. As a guide, a 1D attenuator can reduce noise output by around 8dB, while a 2D attenuator might achieve reductions of 10 to 12 dB. These numbers depend on the fan and attenuator details.

Of course, the attenuators would be subject to the same marine environment as all other equipment and this needs to be considered in selecting the materials for the casing, the perforated plate and the fill.

3.5 An Ideal Ship?

There is of course no such thing as an ‘ideal ship’, as the business model for each shipper will bring different constraints, objectives (and cost functions) to the assessment. Nevertheless, since the authors have been asked the question on several occasions, it is clearly a topic of interest and so we attempt an answer. It should be possible to arrive at these answers by consideration of the other material in this report and so this section is not new information, it just offers a short-cut for those who want to quickly know what the authors think it all amounts to. The solution offered will not be ideal in all circumstances but it should generate re-examination of established dogma.

Our ideal vessel is a high sided ship (like a car carrier). Ships of this configuration, with high sides enclosing all livestock decks must have forced ventilation to all areas and are consequently immune from the problems of following breezes or still air that affect unventilated open decks.

Our ideal ship also has a water-tight weather deck below upper decks which are not sea-tight. In this regard it is like a ‘low sided’ ship with the upper livestock decks closed-in using non-structural sheeting. The purpose of the weather deck at mid height is to allow a different approach to ventilation of the relatively closed upper decks while still remaining seaworthy.

The lower decks are ventilated with both supply and exhaust fans in a balanced way, with all fans located on the top cover deck. The compromise between the number of risers and the extent of horizontal supply ducting is a topic for cost minimisation, however to allow the lower headrooms for higher loading, ducting is likely to be limited to runs above fixed pen rails. The exhaust stream would have no ducting, with one exhaust riser for every 4 to 12 supply risers (depending on fan size).

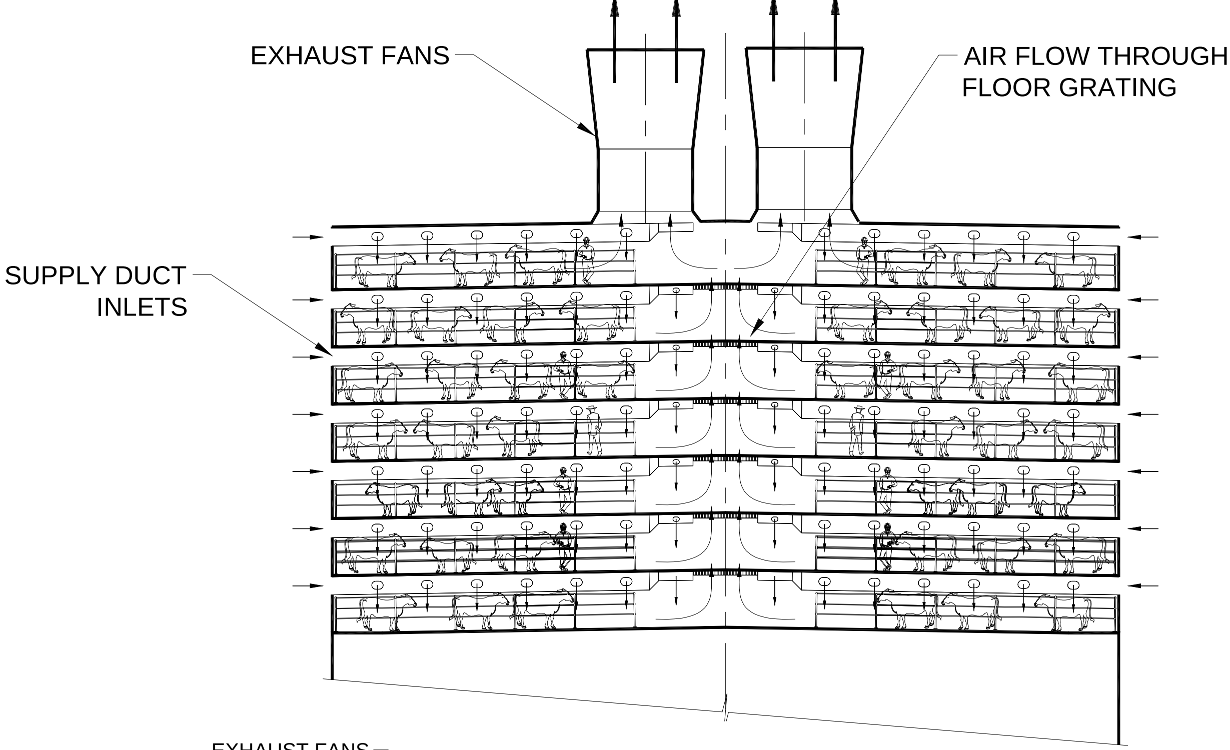
If each supply riser serves a large area on any one deck, then several supply fans (2 to 4) should be “manifolded”. That is, the fan outlets should be interconnected and fans fitted with non-return dampers to give a degree of redundancy should any one fan fail. The extra space and cost required for the interconnection and dampers may tip the balance in favour of more risers, each with a (smaller) supply fan.

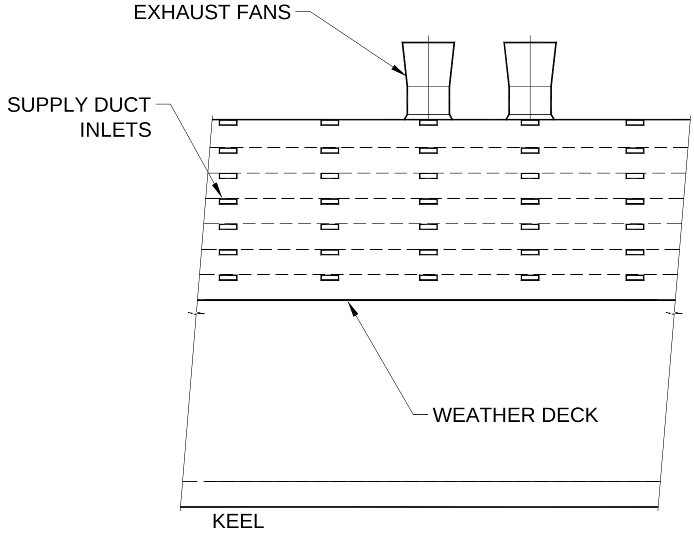
At least two nozzles would direct jets down over the backs of the animals in each pen. The nozzles would have bell mouth intakes and be adjustable in flowrate simply by deforming the outlet area to be elliptical rather than round. If reinforced around the outlets, the risers could also be the structural columns.

The upper decks would be ventilated only by exhaust fans. The supply air would be drawn in through rows of bell mouthed rectangular ‘portholes’ along the sides of the ship and ducted inward from these portholes, over all pens. This requires that the upper decks be relatively closed and means that air would also be drawn in strongly through any open accessways. The exhaust air would rise through gridmesh aisles between the pens such that no ducts or risers are required for the exhaust fans located above the top cover deck. This saves considerable pen spaces.

This approach could also be applied with larger portholes and no ducting. This variation would give no jetting but would allow even higher flowrates for the same power costs. The diagram below shows the upper decks of the ideal ship schematically, in cross section and part side view.

Cross section above the weather deck





Side View

4. Air Flow Facts

4.1 Composition of the Atmosphere

Fresh air is a mixture of gasses dominated by nitrogen and oxygen. For 'dry air' (zero humidity), the breakdown by volume of the relative parts is:

Nitrogen	78.09%
Oxygen	20.95%
Argon	0.93%
Carbon Dioxide	0.03%

There are also traces of neon, helium, krypton, hydrogen, xenon, ozone, radon, methane, nitrous oxide, nitrogen dioxide, sulphur dioxide, ammonia, carbon monoxide and iodine.

Nitrogen is relatively unreactive, only forming different compounds at high temperatures in internal combustion engines or lightning for example. As such, it is essentially an inert 'filler' in the atmosphere for our purposes. It carries away heat, water vapour and pollutants, but does not react significantly. Argon, helium, neon, krypton, xenon and radon are the so called noble gasses which are so unreactive that no natural compounds are known. Carbon dioxide is of interest, however the low level in fresh air (0.03%) is not significant in itself, it is just a number from which to assess increases. That just leaves oxygen, which of course is required for all bodily processes and is converted to carbon dioxide in the body and exhaled.

Of course, real air contains water vapour as well. The amount of water vapour is given by the 'absolute humidity'. The upper limit on absolute humidity before condensation occurs depends on temperature. For example at 30^0C, the most water that can be dissolved in air (100% relative humidity) is 2.74% by mass or 4.4% by volume. From this, it is apparent that water vapour is only ever a small part of fresh (or polluted) air.

For reference, the standard atmospheric pressure at sea level is recognised as 101.325kPa (or 1013 hecto-Pascals if you watch the weather on TV). The corresponding density at 20^0C is 1.2kg/m^3. As above, this figure varies a little with temperature and humidity, however the figure of 1.2kg/m^3 is normally used as the basis for fan performance data.

4.2 What is a Gas?

In fluids (gases and liquids), the molecules are not uniquely attached to adjacent molecules but are free to slide around. In liquids, the spacing of molecules is more or less fixed so that the volume of a mass of liquid does not change much with temperature or pressure. In gases, the molecules are widely spread and "bounce" around off each other and any surfaces with an energy level that is determined by the temperature. The continual bouncing on surfaces by gas molecules is felt by the surface as the gas pressure. If there are more molecules in a volume (higher density), or they are "bouncing" faster (higher temperature), then the pressure will be higher.

Because gas molecules are widely spaced, the density of gases is generally much less than for liquids. Water is about 1,000 times more dense than water vapour (steam) at atmospheric pressure and temperature.

Although, in general, the molecules' spacing and density is highly variable for gases, the variation of air density on ships is so low that the air (gas) can be looked on as a low density liquid for calculation purposes (see Section 4.4).

4.3 Air Flow Friction

Very viscous liquids on a small scale (like honey on a knife) demonstrate 'laminar' flow in which the flow paths of individual bits are smooth, and streamlines don't cross over each other. By contrast, runny liquids (and gases) on larger scale exhibit fully turbulent flow in which a chaotic procession of eddies on all scales ensures rapid mixing of the fluid, in our case across the duct. Air is relatively runny (compared to honey) and the scale of ship ventilation ducts means that all mechanical ventilation flows on ships are fully turbulent.

This means that the flow friction is not so much to do with molecules sliding past each other. The effective friction is due to the turbulent eddies mixing the slow flow near the duct wall with the faster flow in the middle of the duct.

A feature of fully turbulent duct flows is that the pressure drop along the duct is proportional to the square of the velocity (or flowrate). That is; doubling the flow speed (with double the flow) increases the pressure drop by a factor of four. A 10% increase in velocity gives a 21% increase in back pressure.

The relationship between pressure drop, duct size, duct roughness and the square of the velocity is well described in many elementary fluid mechanics texts. The essential relationships are also embodied in industry specific calculation aids such as the ‘ductulator’ for air conditioning or ‘poly pipe’ flow tables for farm irrigation design.

4.4 Fan Power

The air flow power delivered by the fan is equal to the air flowrate times the pressures rise across the fan. The pressure rise across the fan obviously equals the pressure loss through the rest of the ducting (for holds at atmospheric pressure). Section 4.3 noted that, for a given duct, the pressure loss is proportional to the square of the flowrate. As pressure is multiplied by flowrate to get air power, the air power is proportional to the cube of flowrate (or velocity).

Because of this, it is important to consider fan power when designing the ductwork. A 10% increase in duct area (factor of 1.1) can decrease fan power for a given flowrate by a factor of 1.331. That is; with a 10% duct area increase, the power required to drive the ventilation could be reduced to three quarters of the prior value.

The above discussion moved from ‘air power’ to ‘fan power’ without explanation. Fan power (the input power) is larger than air power (the output) because of inefficiencies of the fan. Fan efficiency may be up around 70% but should not be much less than 60% if the system is designed carefully.

4.5 Humidity, Density, Pressure Change and Flow Resistance

The variation in absolute humidity observed at sea and below decks results in a density change of less than 0.5%.

The variation in atmospheric pressure results in density variations less than 2%, while the pressure changes through fans and ducts will typically generate a density change of less than 0.5%.

The change in viscosity which accompanies these changes is not significant.

The flow resistance of the air is a function of the density. The flow resistance is essentially unaffected by changes in humidity, pressure or temperature seen on ships. That is, the air does not get heavier, harder to move or cause blockage by changing its properties below decks.

However, the slight changes in density can drive gentle circulation currents within decks where there is no active jetting or stirring. This is discussed further in Section 2.7.

The small changes in density also mean that no extra air is ‘stored’ below decks. The flowrate out will equal the flowrate in at all times.

4.6 Fans and Rain

One reported purpose of the 'mushroom cap' intakes (see Section 2.1) is to prevent the entry of rainwater. The first point is that fans and motors chosen for the marine environment should be unaffected by splashing water. In fact, rain may be beneficial in removing salt deposits.

The heaviest rainfall is around 100mm in one hour. In conventional units, this gives the rate of accumulation of water as 0.000028m/s. A fan takes in air at around say 20m/s. This means that an unprotected fan would ingest an air-water mix which is only about 1.4 parts per million of water by volume or 0.12% water by weight. At this level, the water is only a minor impurity and of no real consequence to the fan.

For a 1m diameter intake, the heavy rain brings water into the duct at a rate of 22ml per second, or 79 litres per hour, or 10 litres (a bucketful) in 7 minutes or so. This last figure points to a quick method for demonstrating that the fan will not be affected. The water accumulation is obviously not significant in terms of the bilge capacity or pumping rates.