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DESIGN OF A SUBMARINE MAIN BALLAST BLOWING SYSTEMS

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ABSTRACT

A submarine ballast system represents a combination of dedicated equipment and piping in which the main circulating fluid is either sea water straight from the submarine exterior or air which is compressed at high pressures and then it is stored in pressure vessels onboard. These fluids are, then, introduced in or extracted from various tanks located strategically onboard the submerged vehicle. Because water cannot be compressed and because of it's density, it will require large amounts of energy and pumps to be able to move all the water within the system in a short period of time that is required for surfacing a submerged vehicle. Therefore, compressed air is favoured for the main deballasting because of the air's capability of being stored at high pressures and displacing water in a fast manner once it is fed into the ballast tanks, thanks to it's ability to expand as the submarine emerges and the surrounding water pressure drops. In addition, the compressed air systems must operate for at least a normal surfacing from periscopie depth, but also for surfacing from the maximum depth in the case of an emergency. From an engineering standpoint, ballast tank blowing systems are complex, but nevertheless are vital, for allowing the maneuvering of the submarine and it's bouyancy within the water it navigates, regardless if it's in a surfaced or submerged condition and must be done in the smoothest and with as little noise as possible. The requirements of designing and calculation of such systems are covered by the Class and Administration rules and regulations.

Keywords: submarine, submerged vehicle, ballast system, compressed air systems.

1. INTRODUCTION

The process of diving and surfacing constitutes a highly important maneuver in the movement of a submarine. During diving operation, the center of gravity and the center of buoyancy, which are, let's say, "special" in a submarine, are in constant change while seawater floods the main ballast tanks. Therefore, the control of the diving-surfacing mechanism, through adjusting the water levels inside the tanks might seem easy. However, in practice, it has been proven that multiple parameters must be determined by professional design, where practical experimentation of the theoretical elements is necessary for verifying the efficiency of these systems. Ussualy, a submarine must have fast diving abilities, but more important is that it must be able to dive in a stable and silent manner. This aspect can be achieved through a precise control of the relationship between it's mass and buoyancy. This paper will approach such a design of a main ballast system tipically used in a single hull, diesel-electric submarine, able to dive at a maximum depth of 270 meters.

2. FUNCTIONING PRINCIPLES

The analyzed submarine is of a single hull type and the main ballast tanks are located outside of the pressure hull, at the aft and fore of it's extremities, making a total of two main ballast tanks of different capacities,with the fore main ballast tank being the larger one, as it is shown in figure 1.

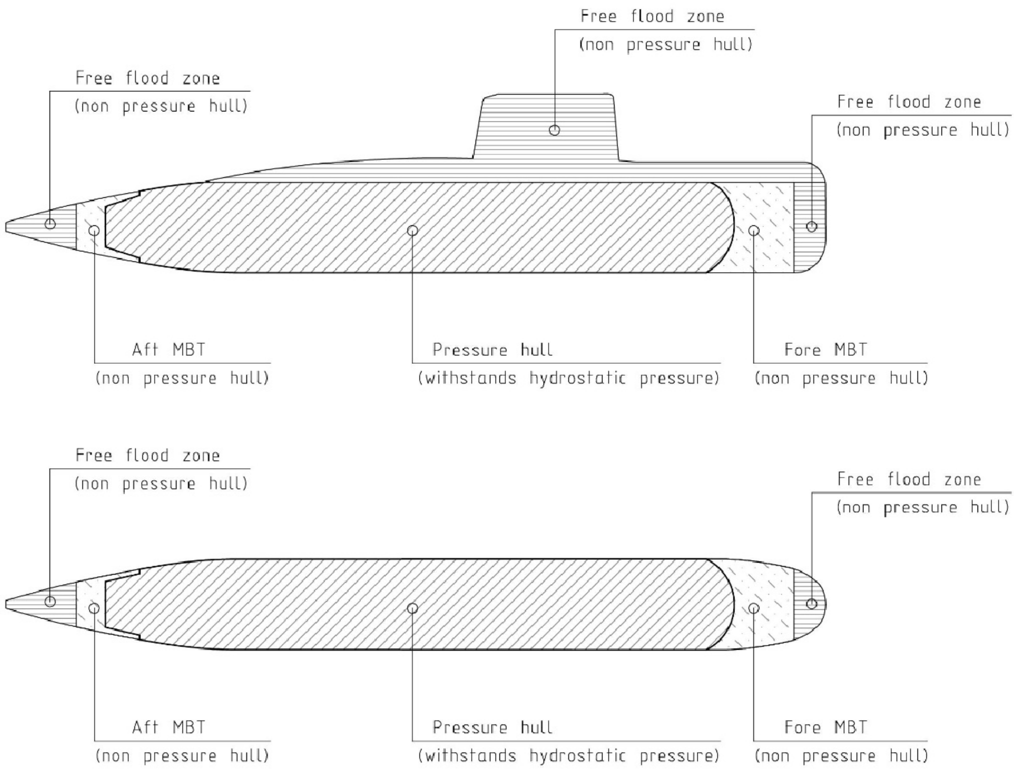

Fig. 1 Ballast tanks arrangement onboard the submarine

Both main ballast tanks are equipped with flood ports at the bottom and vent valves at the top. Flood ports have the purpose of introducing or releasing water from within the tanks, depending on the desired maneuver, while the vent valves have the purpose of releasing air to allow the beginning of the diving procedure or to contain the air released by the compressed air system, for the surfacing maneuver. For the diving procedure, the flood ports will be in open position the entire time of the maneuver to allow the water to enter the tanks, while the vent valves are in open position, to release the air contained within the tanks, thus making the submarine to become neutrally buoyant and and to be able to dive.

Opposite of the diving procedure, for surfacing, the flood ports will be in the open position and the vent valves will be fully closed. Compressed air will be introduced in the tanks, and the fact that the vent valves are fully closed, the air can only expand and displace the water that will be released through the flood ports, thus making the submarine positively buoyant and being able to ascend, regardless of depth.

For these operations to take place in safe conditions and for the tanks to work simultaneous, the flood ports and vent valves must have a size large enough to avoid any pressure accumulation. The size of the flood ports will be directly influenced by the flow of water exiting the tanks in the adopted timeframe. Typically, the flow of water might be considered somewhere between $2 \div 3$ m^3/sec, depending on the design of the compressed air systems. It is to be noted that a smaller size of the flood ports will allow for a smaller water flow allowing for the air to create overpressure when it is introduced into the tanks. This will affect the tank structural integrity and also will affect the blowing process altogether. So, to avoid these effects, sizing of the flood ports must be determined precisely with the addition of an overpressure safety factor when desinging the ballast tanks and the structure of the flood ports. One more aspect regarding the flood ports is that they are located outside and will generate noise when the water is flowing in or out of the tanks. This can be avoided by making them as small as possible, and installing as many flood ports as it is needed to reach the total calculated area.

3. POSSIBLE ARRANGEMENTS

Older submarines have had compressed air systems comprised of compressed air storage bottles from which the distribution of air to the tanks were made through pipes joined by distribution manifolds located inside the command and control compartment. This was considered as being the remote access of the valves allowing for the air to flow within the pipes. In contemporary times, thanks to automation, these systems have become much more simplified because of the valves having different actuating systems allowing for the remote access to be made via computers and software, thus improving valve response time and precision. Nevertheless, the valves need to have locally manual override operation, usually with the same source of power as the remote operation, for when the remote operation devices are not available. Typically, main ballast blowing is made via two compressed air systems, one being for normal conditions at periscope depth and one for emergency conditions used to blow the tanks at any depth when an emergency situation arised. In figure 3.1, it is shown a system arrangement for normal conditions in which there are three groups of compressed air cylinders. The aft ballast tank, being smaller, will be fed with air from the aft cylinder group, while the fore main ballast tank will be fed by two groups of cylinders, because of it being larger and to maintain the same diameter all along the piping system. The arrangement is made in such a way that each group of cylinders will work independently of each other, but in the case that a malfunction is to arise to a group of cylinders, the other groups will be able to take over the task of the defective group. This will be made by interconnecting the groups via a pipe main as shown in figure 3.1. The arrangement of the system for emergency condition is shown in figure 3.2 and is similar with the system for normal conditions, with the difference that the air must not be lowered to a pressure that is less than the cylinder storage pressure, thus, the absence of the pressure reducing valve is imposed. When blowing the ballast tanks in normal conditions, due to the compressible nature of air and to preserve the air pressure for multiple blows, the tanks will be emptied of water at about half of the tank capacity. This condition of half blow will determine an incomplete evacuation of the water, thus requiring a system designed to allow for a complete blow of the tank. These systems are typically designed to operate only with low pressure air, in which an air blower takes air from the submarine's atmosphere and feeds it into the ballast tanks. It must be noted that because the blower takes air from the submarine and may lower the breathable air and conducting to a vacuum onboard, it will operate only when the submarine is at periscope depth and the hatch of the superstructure is open to allow for the atmospheric air to enter. Such a system arrangement is presented in figure 3.3.

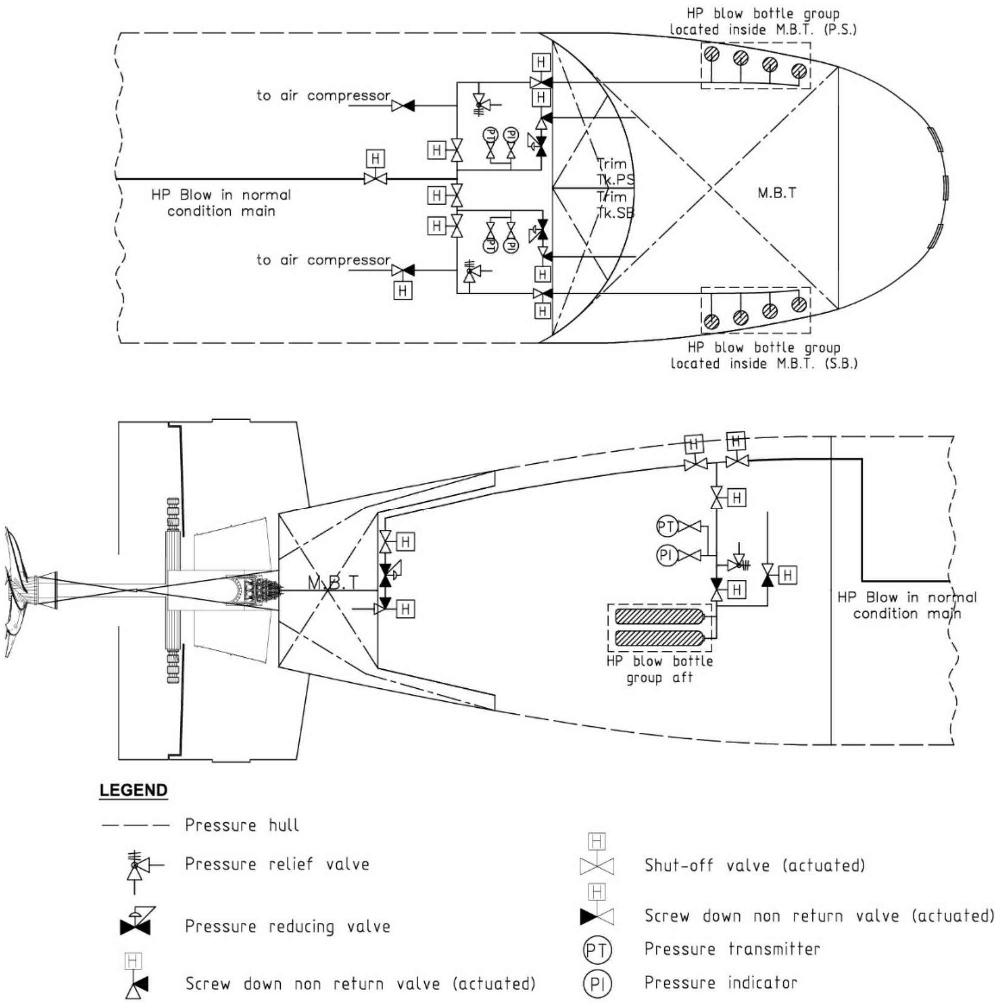

Fig. 3.1 Arrangement of the HP blowing system for normal conditions

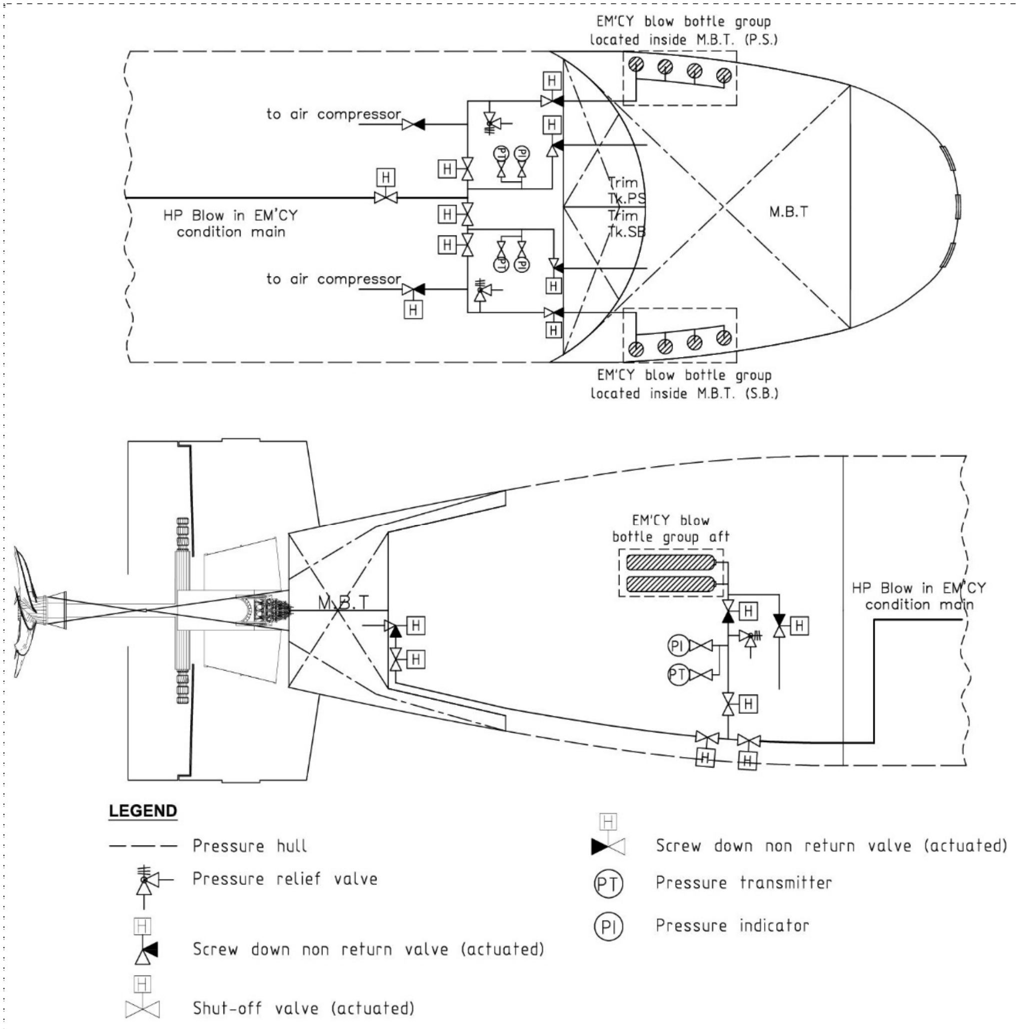

Fig. 3.2 Arrangement of the HP blowing system for emergency conditions

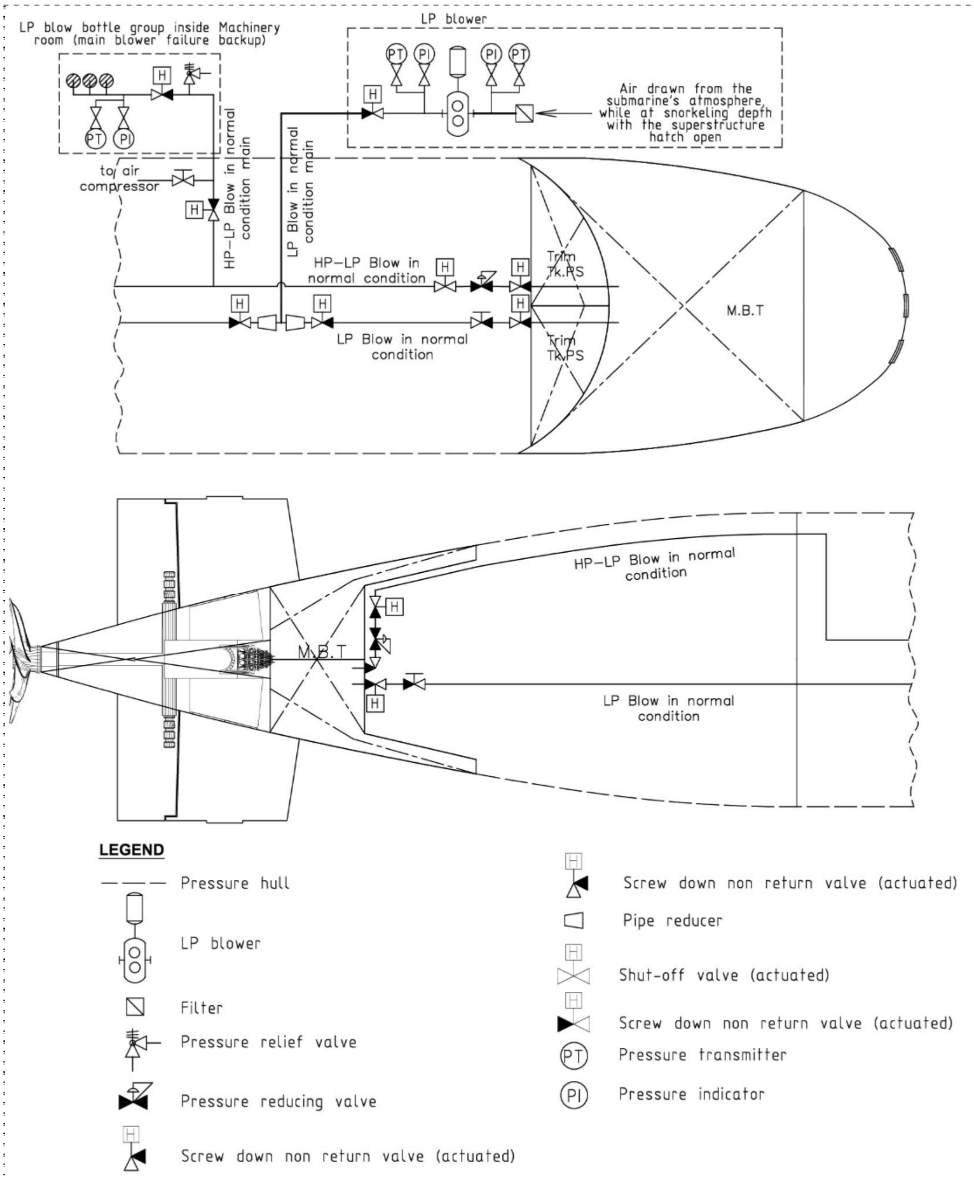

Fig. 3.3 Arrangement of the HP-LP blowing system

4. DESIGN OF AIR SYSTEMS

The first step into desinging a compressed air system for a submarine is to determine the volume of the air needed to fill the ballast tanks and the pressure it needs to operate at, to be able to displace the water within the tanks. When calculating the required air volume to fill a tank at atmospheric pressure it will be taken into account that a safety factor must be applied (formula 4.1). These safety factors are added presuming that the compressed air piping is not perfectly sealed during outfitting and air losses might inevitably occur. These safety factors will be chosen by the engineers and they depend on the system's specific and it's complexity.

$$V_{air_{MBT}} = V_{MBT} \cdot F_s \; [m^3] \quad (4.1)$$

where, $\mathbf{V_{air\ MBT}}$ – required air volume at atmospheric pressure [m^3], $\mathbf{V_{MBT}}$ – main ballast tank volume [m^3], $\mathbf{F_s}$ – safety factor.

Knowing the required air for the ballast tanks, at atmospheric pressure, the required air for a half blow in normal condition at periscopic depth and for a certain number of resurfacing maneuvers, the total volume of air needed for normal blowing can be calculated with formula 4.2.

$$V_{air_{MBT_{normal}}} = \frac{V_{air_{MBT}}}{2} \cdot \Delta p_p \cdot n_{surf} \; [m^3] \quad (4.2)$$

where, $\mathbf{V_{air\ MBT\ normal}}$ – required volume of air at periscopic depth [m^3], $\mathbf{\Delta p_p}$ – hidrostatic pressure at periscope depth [bar], $\mathbf{n_{surf}}$ – number of resurfacing maneuvers.

Hidrostatic pressure can be calculated using formula 4.3.

$$\Delta p = \rho \cdot g \cdot h \; [\text{bar}] \quad (4.3)$$

where, $\boldsymbol{\rho}$ - water density [kg/m^3], $\mathbf{g}$ – acceleration due to gravity, $\mathbf{h}$ – depth of the submarine measured from the base line.

Similar to blowing in normal condition, the blowing at emergency condition will be made at a much larger depth. The pressure at wich will be calculated, can be taken at the crushing depth. One aspect that must be taken into account is that the maneuver requires large amounts of air to be stored onboard for the operation to be effective. But, since space is a luxury on a submarine, the air capacity stored onboard will be used only for one emergency surfacing. In this situation, we won't be able to displace the entire volume of water with air, at the maximum depth. It can be assumed that the volume of compressed air to be fed into the tanks, will have to displace only about 20% of the water while the accumulated air pressure, due to the storage pressure which is higher than that of the water comlumn, will progressively push the water out as the submarine rises. At first, the ascend will be slower, but as the water is displaced by the expanding air, the speed of the ascent will increase, allowing for a fast surfacing. The volume required for blowing at the emergency condition is calculated using formula 4.4.

$$V_{air_{MBT_{em'cy}}} = \frac{V_{air_{MBT}}}{5} \cdot \Delta p_{max} \; [m^3] \quad (4.4)$$

where, $\mathbf{V_{air\ MBT\ em'cy}}$ – required volume of air at periscope depth [m^3], $\mathbf{\Delta p_{max}}$ – hidrostatic pressure at maximum / crushing depth [bar].

After determining the air capacities required for blowing the ballast tanks for normal and emergency conditions, the aspect of storing it onboard arises. The air can be stored into compressed air storage cylinders at high pressures, around 275 bar, which in turn, are placed outside of the pressure hull, usually in the main ballast tanks. In this case, the cylinders for the fore ballast tank can be installed right inside of it, while the aft ballast tank can not hold such recipients due to the shape of it, leading for the recipients to be installed inside the propulsion compartment allowing for a minimum length of piping, as it is shown in figures 3.1 and 3.2.

The recipients will be selected in such a way that they will fit at the installing location, allowing for enough clearance in the case of removal of the recipient for any purpose, like servicing. Knowing the internal volume of the cylinder, the required air capacity for each condition and the storage pressure, we can calculate the required number of compressed air storage cylinders using Boyle's Law (formula 4.5).

$$p_1 \cdot V_1 = p_2 \cdot V_2 \quad (4.5)$$

where, $\mathbf{p_1}$ – pressure of uncompressed air [bar], $\mathbf{p_2}$ – storage pressure [bar], $\mathbf{V_1}$ – volume of air [m^3] at pressure p_1, $\mathbf{V_2}$ – volume of air [m^3] at pressure p_2.

After calculating the volume of air at storage pressure, V_2, all that is left is to calculate the ratio between this volume and the internal volume of the recipient, to determine the number of the cylinders. Another aspect regarding air pressure is that the air pressure inside the storage cylinder required for the last blow, must not drop bellow an imposed pressure and is regulated by the classification societies. To verify this, the ideal gas law of state in formula 4.6 can be used.

$$p \cdot V = m \cdot R \cdot T \quad (4.6)$$

where, **p** – imposed air pressure [bar], **V** – volume of ballast tank [m^3], **m** – mass of air required for the last blow [kg], **R** – air constant]kJ/kgK], **T** – air temperature [°K].

After solving every unknown factor regarding the compressed air and the storage of it, the piping systems must be calculated. An important aspect in sizing the piping is that the air, as it's getting cooler, will expand. This fact in combination with the high velocity due to pressure, may lead to the freezing of the air withing the pipes, which is an undesirable effect in a submarine, causing for it to not beeing able to rise to the surface. This effect can be neutralized by mantaining a constant diameter along the piping system on it's entire length or to lower the diameter in the direction of the air flow. The condition that must be met is stated in formula 4.7.

$$\frac{\pi \cdot d_1^2}{4} \cdot n \geq \frac{\pi \cdot d_m^2}{4} \equiv \quad (4.7)$$

$$d_m \leq d_1 \cdot \sqrt{n}$$

where, $\mathbf{d_1}$ – storage cylinder branch diameter, $\mathbf{d_m}$ – main pipe diameter.

Having that in mind, we can calculate the pipe diameter by knowing air characteristics and the required flow using formula 4.8.

$$d = 8.64 \cdot \sqrt{\frac{Q \cdot T \cdot Z}{P \cdot v}} \quad (4.8)$$

where, **d** – main pipe diameter [mm], **Q** – air flow [m^3/min], **T** – air temperature [°K], **Z** – air compressibility factor, **P** – air pressure [bar], **v** – air velocity through pipe [m/s].

Other aspects like pipe wall thickness, joint type and reinforcement are stipulated in rules of the Classification Society, along with other requirements for the system.

5. CONCLUDING REMARKS

When designing a robust and efficient compressed air system for the main for ballasting the main ballast tanks of a submarine, some semnificative chalenges arise, like ensuring the structural integrity of the ballast tanks when they are fed with compressed air, the prevention of air leakages and the elimination of the risks associated with rapid changes of uncontrolled flotability. When designing such a system, besides intensive testing, some fail safe measures and mechanisms must be implemented to allow for a maximum safety condition for the entire submarine and it's crew.

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