Reducing parasitical heat flow to Seabird SBE 38 by means of insulation for thermodynamic efficiency measurements

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1 Abstract

The thermodynamic method for measuring the hydraulic turbine efficiency is a reliable and well-established method. It evades the need for directly measuring the turbine discharge. Instead, the inner energy of the fluid is determined before and after passing the turbine. This requires precise measurement of the water temperature. In many cases a flow sample, named secondary flow, must be extracted from the primary flow i.e., the turbine discharge. This makes it possible to determine the inner energy of the water outside of the primary flow but imposes that the inner energy must not be changed. The main complication is heat flow from the ambiance into the secondary flow.

The Seabird SBE 38 is a high-precision digital thermometer. Even though originally developed for maritime research its characteristics make it well suitable for efficiency measurements in hydro power applications. However, the SBE 38 is being criticized for high secondary heat flow originating either from the ambiance and entering through the sensor housing or originating from the internal electronics.

In this paper we discuss a scientific and systematic approach to investigate several different insulation methods of the entire secondary conduit and water-cooling of a SBE 38 with a second extraction from the primary flow. The research is undertaken by Nathanael Weckerlein for the obtaining of his degree as Bachelor of Science in mechanical engineering. His thesis and experiments are supported by Marco Eissner. His findings show great potential for improving the SBE 38 performance and effectively cutting down the secondary heat flow. Due to the comparative nature of the experiments, it is possible to identify other issues with the precision of the secondary flow measurement method and propose further improvements that can be adopted for all measurements that rely on the extraction of a sample from the primary turbine discharge.

The notation of physical properties in formulas follows the definition of IEC 60041.

2 Introduction

The thermodynamic method allows cost-effective and straightforward efficiency measurements. This is because the turbine discharge does not have to be measured directly. Instead, the energy of the water before and after passing through the turbine is measured. This requires highly accurate measurements of the temperature of the water that enters and exits the turbine. In most cases, a sample of the water is continuously extracted in a so-called secondary flow. The temperature, pressure and the volume rate of the water is then measured in a vessel, apart from the primary flow. This procedure requires that no energy is exchanged with the secondary flow.

In order to limit this parasitical heat flow to or from the secondary flow, one can insulate the pipes and the vessel itself. Another approach is to supply the same temperature on the outside of the pipes and hoses and therefore limit heat exchange with the ambiance. Both methods are applied and tested, and the results given in this paper.

The Seabird SBE 38 is a high precision digital thermometer which is suitable for efficiency measurements by means of the thermodynamic method due to its high temperature resolution, accuracy, and pressure resistance. However, since it contains active electronics that process the signal it emits heat to its surroundings. Therefore, not just isolating the vessel and the sensor from the ambiance, but actively cooling the sensor and keeping it at the temperature of the probed water deems a more promising approach. Another drawback is the large housing that promotes heat flow from the ambiance through the housing into the sample. This is not a problem when the sensor is fully submerged e.g., in marine applications, but can contribute to parasitical heat flow in an efficiency measurement setup with vessels.

This paper presents the works and results that were undertaken in investigating different approaches to reduce parasitic heat flow and thus increase the accuracy of the results.

3 Method

First the thermodynamic method is quickly revisited to help understanding the then following considerations. Then the approaches for reducing the heat flow and the method for comparing those approaches are presented.

3.1 The thermodynamic method for efficiency measurements

The method is stated in IEC 60041 “Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines”. The method will be briefly presented to provide a basic understanding.

A turbine is drawn in Figure 1 with its properties as an open thermodynamic system. Energy enters through the high-pressure side i.e., section 1, representing the spiral case inlet. It leaves the system either through the shaft as mechanical power P_m or as residual energy through the low-pressure side i.e., turbine outlet section 2 which is the draft tube. Energy exchange on the surfaces of the conduit, spiral case and draft tube between sections 1 and 2 are not considered.

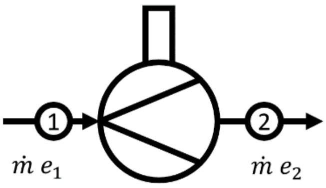

Figure 1: A hydropower turbine as thermodynamic system

The balance of energies of the system as drawn in Figure 1 yields

$$\dot{m}\, e_1 = \dot{m}\, E_m + \dot{m}\, e_2 \,. \tag{1}$$

The hydraulic efficiency is given by the relation of the extracted specific energy E_m over the available specific energy

$$\eta_h = \frac{E_m}{e_1 - e_2} \,. \tag{2}$$

The specific energies e_1 and e_2 are determined by measuring the water temperature, static pressure, the velocity of the secondary flow as well as the elevation of the vessels. The mechanical specific energy must be estimated with a sufficient certainty based on measuring the active power of the generator considering the losses that occur between the runner and the generators terminals.

Measurement of the specific energies e_1 and e_2 is typically established through extraction of water samples at sections 1 and 2 into vessels. The vessels are referenced with an additional number appended to the number of the section. In a prototype measurement more than one sample is taken at each reference section. However, only one sample per section will be considered here. This extends the thermodynamic model described in Equation (1) to what is drawn in Figure 2.

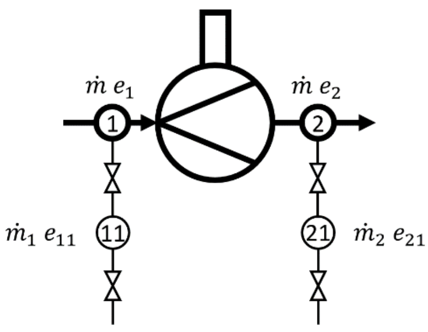

Figure 2: thermodynamic system of a turbine with sample extraction into measurement vessels at the reference sections.

For means of efficiency calculations not the absolute value of energy e_i is of interest, but the difference between the reference sections $E_{i-j} = e_i - e_j$. Thus, below the equation for calculating the difference in specific energy between two points i and j based on the measured quantities is given

$$E_{i-j} = \bar{a}(p_i - p_j) + \bar{c}_p(\Theta_i - \Theta_j) + \frac{v_i^2 - v_j^2}{2} + \bar{g}(z_i - z_j)\,. \tag{3}$$

The overbar over a and c_p mean, that they can be calculated or read from a table based on the mean values of their variables at the measurement section e.g., $\bar{a}(p) = a(\bar{p}) = a\left(\frac{p_i+p_j}{2}\right)$.

It is assumed, that the total energy does not change due to the extraction, thus

$$e_1 = e_{11} \text{ and } e_2 = e_{21}. \tag{4}$$

This assumption generally does not hold true due to heat exchange with the ambiance. The IEC 60041 standard is not ignorant of this. It states repeatedly that good insulation of the pipes and vessels must be assured. However, no practical advice is given on effectively insulating pipes and vessels. The objective of the research in this paper is to provide definitive recommendations regarding effective insulation practices. The heat exchange occurring between the points of extraction and the respective vessels is explored and it is examined how the differences in energies e_i and e_{i1} and can be limited.

The issue of parasitic heat exchange into the secondary flow is addressed by IEC 60041 with a correction method. The idea behind this method is simple: while the operation point of the turbine is kept unchanged ($e_i = \text{const.}$), the total energy of the secondary flow (e_{ij}) is measured multiple times while changing the rate of the secondary flow. With increasing flow rate, the time available for heat exchange with the ambiance is becoming less and thus the parasitic heat flow is also reduced. Higher flow rates mean higher friction, thus higher loss of pressure and dissipation of pressure energy into heat. By the theory however, the energy is converted and not "lost". Thus, the assumption in Equation (4) is not violated.

The standard proposes to plot the energies thus recorded over the reciprocal of the secondary flow. By connecting the dots with a line and extrapolating it to $1/q_i = 0$ the value of the desired energy without parasitical heat can be determined.

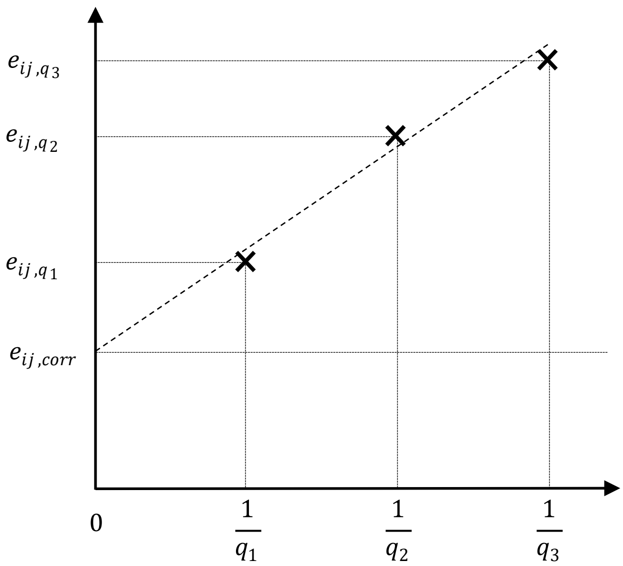

Figure 3: Graphical method for correcting the specific energy e_{ij} for parasitical heat flow as proposed by IEC 60041.

In practice one will find that the dots do not line up linearly when the secondary flow is sufficiently altered. This is because not all of the dissipated energy is conserved in the system that defines the secondary flow. More on that is given in chapter 5 "Further learnings".

3.2 Approaches for insulating the measurement vessel

We have stated that a fundamental assumption is made that energy is conserved in the secondary flow. Some pressure energy will be dissipated into heat due to friction and the velocity can change, therefore changing the static pressure. The sum of energies will however remain the same if no energy is transferred over the system boundaries. Such can happen in terms of heat flow which is further called parasitic heat flow.

Heat may be transported through conduction or radiation. Also, heat may be introduced through a local heat source. These three possible paths for parasitic heat flow lead to three approaches to inhibit it.

Conduction of heat from the ambient air can best be reduced by adding insulating material around the apparatus. A shell made from polyisocyanurate (PIR), which is a hard foam with very low heat conduction, was constructed around the vessel and pipes for testing against conduction.

Radiation can be reduced by a reflective layer that shields off the surfaces and reflects the infrared waves (heat radiation). For the purpose of testing against heat radiation a space blanket (also known as emergency blanket) was used. This is a thin plastic film with a metal layer which reflects almost all oncoming thermal radiation.

An internal heat source can only be counteracted by actively removing that heat away from the thermometer, i.e. by cooling the apparatus. For this purpose, the vessel is equipped with an additional hood. This allows to lead water from the primary flow, thus at the same temperature, over the thermometer's body and therefore cool it. The hood is designed in a way that the cooling water can be at the primary pressure. Therefore, the cooling water is not heated due to expanding it to a lower pressure. However, heat exchange of the cooling water with the ambient air can occur and therefore can compromise the effectiveness of the approach. The cooling hood does not only remove heat from the internal electronics, but it counteracts also against heat flow from the ambiance through the sensor housing.

3.3 Method for relative comparison of insulation setups

The test is designed under two guiding principles: 1) it should mimic a real thermodynamic efficiency test on a hydro power asset and 2) the different setups must be compared directly by measuring simultaneously and under conditions as similar as possible.

An installation is made on a model turbine test rig where conditions are closely monitored and controlled. Water is transported through a circuit while the water's temperature is kept constant. After passing through a pumping stage and the main conduit, where the probe and the vessels are installed, the water is guided to a model scale Pelton turbine.

A schematic sketch of the extraction setup is shown in Figure 4. Both setups are based on a shared probe and two vessels which are normally used for prototype measurements. The shared probe is developed especially for this comparative study to provide water with the same specific energy from the main flow to the two setups. One set is declared the reference and remains unchanged over the course of the tests. It does not feature any insulating measures additional to the vessel's original design. The experimental setup is systematically modified to evaluate the various insulation methods.

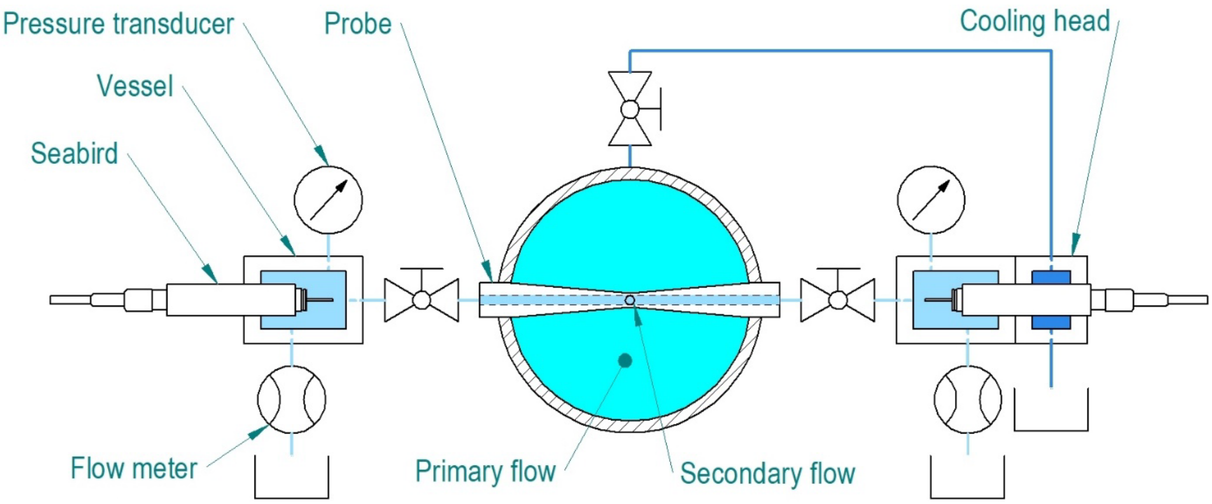

Figure 4: Schematic view of the measurement setup with hydraulic network and section view of the main conduit and shared probe for comparative testing. Left is the reference vessel and right the test vessel shown with cooling head.

Before the comparison of different insulation setups starts, the two vessels are compared at different operating points of the test rig. The test rig can be set to produce different primary flow rates and it can operate at different static pressures. It is found that at low static pressure (equal to $100\ \mathrm{m}$ head) the difference in specific inner energy measured between the two vessels is much higher (up to $11\ \mathrm{J/kg}$ for low flow rates) than at higher static pressures (typically below $3\ \mathrm{J/kg}$ at all flow rates). In order to not overstrain the pumps a medium static pressure (equal to $120\ \mathrm{m}$ head) and a primary flow rate of $80\ \%$ of the maximal possible flow rate are chosen. This equals to approx. $0.281\ \mathrm{m^3/s}$ and a mean velocity of $3.85\ \mathrm{m/s}$ in the main flow.

Every testing day starts with a 1.5-hour relaxation period to achieve thermodynamic stability. After that period no more changes in the measured energies of the vessels are observable.

The experimental set is run without any additional insulation, such that the deviation between the two sets due to uncontrollable influences E_{offset} can be determined and compensated.

Only after this calibration the experimental set is modified such that comparison with the reference set can be initiated.

For every setup the secondary flow rate is systematically varied such that the corrected value E_{corr} can be obtained.

From the corrected specific inner energies E_{corr} and the compensation value between the two sets it is possible to calculate the difference in specific energy between the reference and the measurement vessel ΔE. This value represents the effectiveness of the tested insulation method. Therefore ΔE is used for comparing the different isolation setups with each other.

For the combination of the space blanket and the PIR shell, the space blanket is installed directly on the vessel and below the PIR shell. When the PIR shell is combined with the head cooling, it is adapted in a way that it houses the additional cooling hood. In the same manner the space blanket also covers the cooling hood when installed.

4 Results – Comparison of insulation methods

With the three insulation options and their combinations there are a total of eight different test cases. Figure 5 and Figure 6 graphically display the results i.e., the differences in measured specific energy between reference and measurement vessel ΔE. Also, the total parasitical heat immission to the reference vessel is given on the right ordinate. This allows to further evaluate the insulation in terms of their absolute effectiveness. The error bars on the ΔE-bars give the actual calculated uncertainty for each measured ΔE.

A first observation of the two figures shows that head cooling creates a much higher difference in energy than any other single insulation method or combination of other insulation methods. This observation emphasizes that heat from the internal electronics of the SBE and conduction through the sensor housing can significantly influence the measurements of the temperature if not taken care of.

Surprisingly, adding an additional means of insulation does not always increase the energy difference. This is true for head cooling with PIR shell and the combination of all four insulation methods as well as it is true for the PIR shell only.

With the PIR shell only the energy difference is very low and even negative for 20 and $30\ \mathrm{l/min}$ secondary flows. This means that more parasitical heat entered the measurement vessel which was insulated more than the reference vessel. The behavior was verified by additional tests and is not due to extreme uncertainty or random error. A possible explanation of this peculiar behavior may be given by the fact that the addition of the insulation shell not only suppresses heat conduction from the ambiance to the insides. It also enlarges the outer surface area which increases radiation and convection with the ambiance. It is therefore possible that the total heat immission increases even though a layer of insulation was added.

The highest total energy difference was obtained by the combination of head cooling and the space blanket. Especially with high secondary flows, the heat immission could virtually be zeroed by this method.

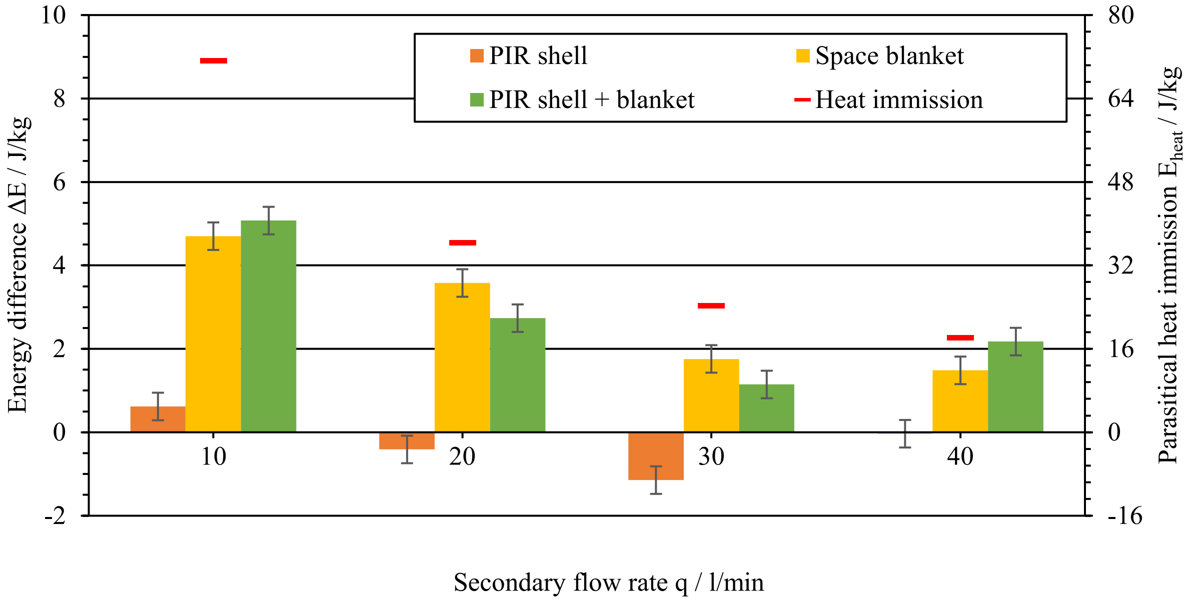

Figure 5: Comparison of insulation setups without a cooling head. Given is the difference in measured specific energy between reference and measurement vessel on the left ordinate, and the parasitical heat flow to the reference vessel on the right ordinate. Note that the scaling differs between the ordinates by a factor of 8!

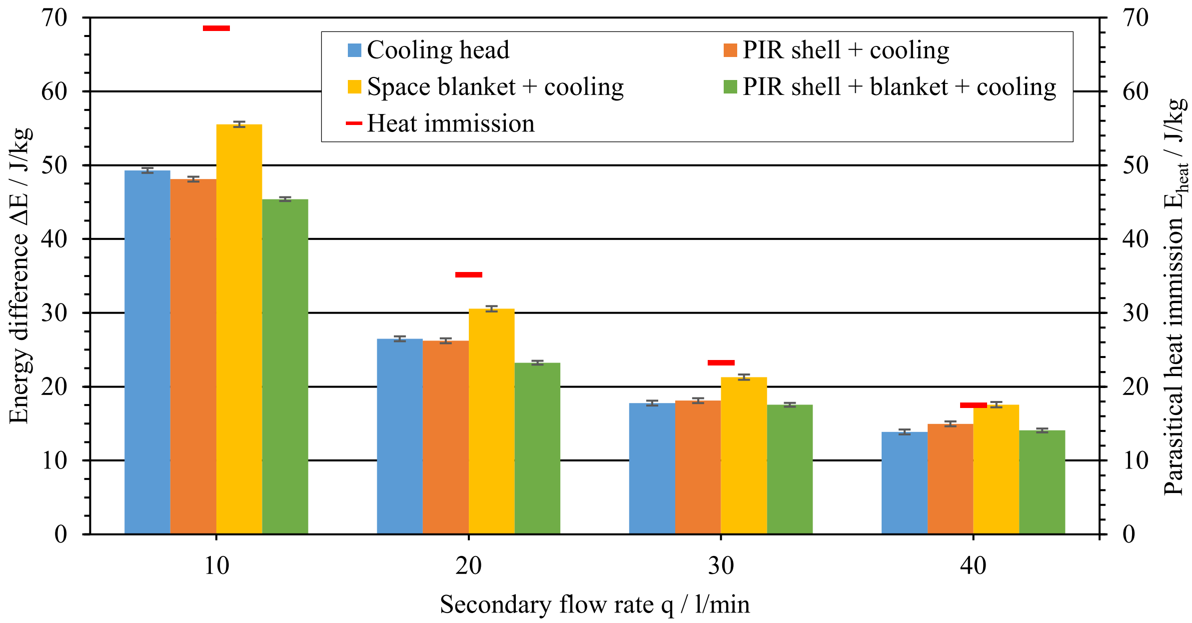

Figure 6: Comparison of difference of specific energy of different insulation setups with cooling head on the left ordinate. On the right ordinate with the same scaling is given the parasitical heat flow to the reference vessel.

5 Further learnings

The sample probe is designed and manufactured specifically for this test. Initially, the measured specific energy e_i was changing excessively with the secondary flow rate. The reason for this is tracked down to very sharp edges on the orifice and the junction of the longitudinal and transverse bore. This rose our attention to dissipation in the sample probe. The problem here is that the sample probe itself is very poorly insulated against the primary flow. When dissipation is high in the region of the probe that is immerged in the primary flow, a lot of that friction heat is conducted into the primary flow! Therefore, the assumption of energy conservation in the secondary flow (see Equation (4)) is violated.

Due to this mechanism the measured specific energy e_i drops with increased secondary flow. This is opposed to the theory by which the parasitical heat flow is reduced with increased secondary flow due to the reduced time for heat exchange. (This assumes that the parasitical heat flow is positive in the sense from the ambiance into the system. This is usually the case since the surrounding temperature is typically higher than the water temperature.)

Even though this observation is nothing unexpected, the extent of the influence of some sharp edges on the losses had been underestimated by us. To our surprise, the IEC 60041 is not raising awareness to the issue.

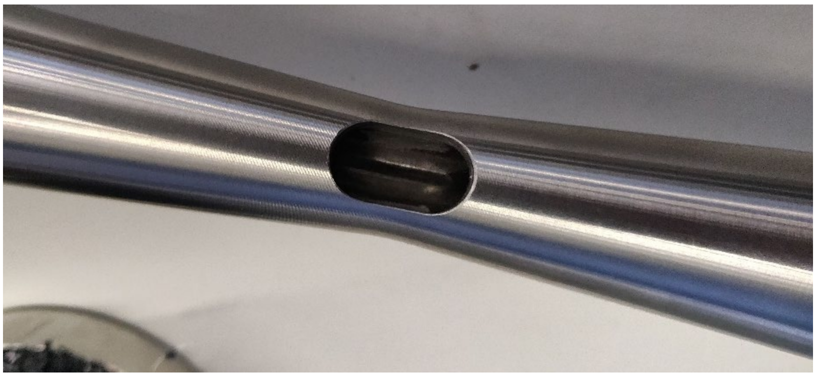

Figure 7: Dissipation of inner energy at the extraction of the secondary flow is significantly reduced after enlarging the probe's orifice into a slotted hole and smoothing out the edges on the outer and inner surfaces.

6 Conclusion

Eight different insulation setups are cross tested in a direct comparison on two identical vessels in a hydraulic model test rig. With the given ambient conditions, the cooling of the head of the Seabird SBE 38 and the addition of a space blanket to the vessel and pipes prove to dramatically reduce the parasitical heat that flows from the ambiance into the sample flow. These means of insulation therefore greatly improve the accuracy of the final results in terms of measured specific energy as well as efficiency.

While the head cooling of the seabird requires additional equipment and an additional water extraction from the main flow, a space blanket can be added at almost no cost and effort.

Further, the experiments highlight the influence of the design and manufacturing of the sample probes. Any sharp edge, a rough surface, or a misalignment of the longitudinal and transverse bore of the sample probe create high energy dissipation. A great part of the heat from this dissipated energy is lost to the main flow because the probe is poorly insulated inside of the conduit. This leads to high offsets and therefore makes the correction energy E_{corr} less precise.

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