CONCEPTUAL DESIGN, SIZING AND THERMAL ANALYSIS OF AN ALERTING SYSTEM FOR MANNED AIRSHIPS

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Abstract

This paper describes an automatic and self-contained electromechanical safety system for manned airships, which alerts the flight crew when the temperature at some point over the envelope exceeds a pre-determined safe limit. The system consists of a thin electrical wire that is looped over the airship envelope along its length, which melts at the location(s) at which the safe temperature is exceeded, and sounds an alarm in the crew cabin. A detailed technical description of the alerting system and all its elements is provided, and a methodology for carrying out sizing of the system, and to carry out thermal analysis is outlined. The methodology is used to size the system for an airship of 30 m envelope length cruising at a speed of 20 m/s at an altitude of 10,000 ft. Results indicate that the mass of the system is a small fraction of the force of buoyancy generated by the airship envelope. Thermal analysis indicates that the alerting system is thermally stable, and despite the fact that current is consistently and continuously flowing in the alarming circuit, the wires are not overheated. The system can be of great help in increasing operational safety levels of a manned airship.

Keywords: Lighter-Than-Air Systems, Airships, Safety systems, Alerting system

Nomenclature

\( T_{Ac} = \) Hottest temperature at the envelope surface (K)  
\( T_{ME} = \) Melting point of the envelope material (K)  
\( T_{SIE} = \) Self-ignition temperature of the envelope material (K)  
\( T_d = \) Temperature at which the thermal degradation of the envelope material starts (K)  
\( T_{MW} = \) Melting point of the material of wire used for envelope circuit (thinner portion) (K)  
\( T_{SIW} = \) Self-ignition temperature of the material of wire used for envelope circuit (thinner portion) (K)  
\( T_{SIG} = \) Self-ignition temperature of the LTA gas filled in the envelope (K)  
\( c_p = \) Specific Heat of the air (J/kgK)  
\( k_a = \) Thermal Conductivity of the air (W/mK)  
\( Re = \) Reynolds number  
\( Nu = \) Nusselt number  
\( Pr = \) Prandtl number  
\( V = \) Voltage of the battery employed in the primary gondola circuit (volts)  
\( V' = \) Voltage of the battery employed in the secondary gondola circuit (volts)  
\( y = \) Gap between the switching plate "a" and the plane of switching plates "b" and "c", after the solenoid of the primary gondola circuit is energized (m)  
\( a, b = \) Dimensions of the airship envelope (m)  
\( L = \) Length of the envelope (m)  
\( D = \) Maximum diameter of the envelope (m)
S = Total outer curved surface area of the envelope (m$^2$)

$l_w$ = Total length of the wire in the envelope circuit (thinner portion) (m)

d = Diameter of the wire in the envelope circuit (thinner portion) (m)

n = Distance measured along the longitudinal axis of the envelope in which one turn of the coiled wire of envelope circuit resides over the envelope surface (meters per turn)

$A_w$ = Cross-sectional area of the wire in the envelope circuit (thinner portion) (m$^2$)

$I$ = Current through envelope circuit and primary gondola circuit (ampere)

$R$ = Resistance of the envelope circuit (ohm)

$B$ = Strength of the magnetic field inside the solenoid of primary gondola circuit (tesla)

$N'$ = No. of turns per unit length in the solenoid (turns/m)

$N$ = Total number of turns in the solenoid

$A_c$ = Cross-sectional Area of the core in the solenoid (m$^2$)

$I_g$ = Initial air-gap between the core and the piston when the solenoid is not energized (m)

$k$ = Stiffness of the compression-spring (N/m)

$F$ = Force acting on piston when solenoid is energized (N)

$Q_{in}$ = Rate of heat generation in the wire of envelope circuit (J/s)

$Q_{out}$ = Rate of convective heat loss from the wire of envelope circuit to atmosphere (J/s)

$A_{ht}$ = Heat-transfer area for the envelope circuit wire (m$^2$)

$\Delta T$ = Temperature difference between the wire and flight surroundings (K)

$h$ = Convective heat transfer coefficient for heat transfer from wire to atmosphere (W/m$^2$K)

$T_s$ = Steady-state temperature of the envelope circuit wire (K)

$T_f$ = Ambient temperature at flight altitude (K)

$t_f$ = Time after initiation of flight at which the envelope circuit wire attains steady state (seconds)

$R_f$ = Electric Resistance offered by the envelope circuit during flight after the steady state is attained (ohm)

$L_c$ = Characteristic length of the envelope (m)

$L_{cw}$ = Characteristic length of the wire for cross-flow (m)

$T_{amb}$ = Ambient temperature at ground (K)

LTA = Lighter-Than-Air

Greek Symbols

$\alpha$ = Temperature coefficient of resistance of the envelope circuit wire material (K$^{-1}$)

$\sigma$ = Density of the air (kg/m$^3$)

$\mu$ = Dynamic viscosity of the air (Pa-s)

$\nu$ = Relative velocity of the Airship w.r.t air (m/s)

$\rho$ = Resistivity of the material of the wire of envelope circuit (thinner portion) (ohm-m)

$\mu_o$ = Magnetic permeability of the free space (H/m)

$\mu_r$ = Relative magnetic permeability of the core or piston material (H/m)

$\sigma_E$ = Envelope specific weight (g/m$^2$)

Introduction

The envelope of an airship is its most crucial component, and hence from operational safety point of view, it is important that the flight crew is always aware of the health of the envelope during all segments of flight. For some reason, if the envelope is being subjected to any hazardous conditions (e.g. excessive stress or temperature), the crew needs to be alerted, so that they can take necessary action before an accident occurs. Temperature at some part of the envelope surface may exceed the safe-limits due to several reasons, for example, generation of excessive heat in the propulsion system, or radiation heat-transfer due to excessive exposure to sun or hot ambient conditions. Any material used to construct the envelope has a characteristic temperature $T_{d}$, above which it starts to degrade thermally and another characteristic temperature $T_{SIE}$, above which it undergoes self-oxidation or self-ignition. Also, most of the commonly used envelope materials are thermoplastic polymers; hence undergo melting at certain temperature $T_{ME}$. Exceeding any of these temperatures may result in massive leakage of the LTA gas out of the envelope, hence loss of buoyancy, and several other risks, as explained in the sections that follow. This paper describes an automatic system that can alarm the flight crew if the temperature of the envelope exceeds dangerous limit at any location on the envelope during flight.

Motivation

Due to scarce availability and excessive cost of Helium, there is increasing pressure on LTA system designers and operators to consider Hydrogen as the LTA gas. Although the regulatory requirements prohibit use of Hydrogen as the LTA gas, recent studies try to highlight that using Hydrogen is not as dangerous as it is thought to be
Multi-chamber envelope configurations have also been suggested to permit partial replacement of the Helium gas by Hydrogen gas [2]. As the naturally occurring reserves of Helium will dry out, there will be an increasing pressure to shift to Hydrogen as an LTA gas for airships, due to its much lower cost, easy availability and better payload carrying capacity.

However, there is always a danger that in these fully (or partially) Hydrogen-based LTA systems, the Hydrogen gas may leak-out to the atmosphere, due to a puncture in the envelope. "T_SIG" of Hydrogen is around 500°C [3], and its ignition in air is a highly exothermic reaction, which can cause the envelope to catch fire. To preclude this possibility, it is important to ensure that temperature at any point of the envelope never approaches this value. It is also evident that even the best of the materials being used these days for envelope-fabrication, (e.g. Kevlar), start degrading considerably as temperature approaches 500°C. One of the following three scenarios can exist while operating an airship;

a) If $T_{AC} < T_{ME}, T_{d}$ or $T_{SIG}$, then there is no danger at all.

b) If $T_{AC} > T_{ME}$ or/and $T_{AC} > T_{d}$ and $T_{AC} < T_{SIG}$, then there will be considerable leakage of the LTA gas into the atmosphere from the envelope, at the location where these temperature conditions prevail. This will lead to loss of buoyancy, but there will be no danger of ignition, unless an electric spark is somehow present.

c) $T_{AC} > T_{ME}$ or/and $T_{AC} > T_{d}$ and $T_{AC} > T_{SIG}$, then the situation is highly dangerous, and there will be an ignition.

**Design of the Alerting System**

This paper explains the design and analysis of an alerting system for operational safety of Hydrogen-based airships operating in condition b) or c) listed above. The system consists of two circuits, viz., the Envelope-circuit and the Gondola-circuit, as described below:

**Envelope Circuit**

As shown in Fig.1, this circuit runs from terminal "A" to the tail and another from terminal "B" to the nose of the envelope along its outer surface. Next, a very thin metallic (or alloyed) wire is wound over the envelope from its nose to the tail in the form of a helical coil. The diameter of this wire is chosen to be so small, that if any point on the wire attains a temperature equal to its melting-point ($T_{MW}$), it should break, resulting in a short-circuit. The material of the wire should meet the following requirements:

- $T_{MW} < T_{SIW} < T_{SIG}, T_{MW} < T_{ME}$ and $T_{MW} < T_{SIW} < T_{d}$. "$T_{MW}$" should not be too low, and must be as close to $T_{SIG}$ as possible, to avoid unnecessary sounding of the alarm.
- Its electrical conductivity should be as high as possible.
- It should not react chemically with the envelope-material up to temperatures somewhat higher than $T_{MW}$.
- It should have high resistance to thermal oxidation in the atmospheric oxygen.

A small gap is to be maintained between the consecutive turns of the coiling, depending upon the desired accuracy in locating the area of excessive temperature increase and reliability-level to be met by the airship. It can be noted that the wire turns lie over the outermost surface of the envelope exposed to the atmosphere, and are held there mechanically with the help of a few light weight wire-supporting structures. There should be provision of thermal as well as electrical insulation between the wire and envelope surface as shown in Fig.1.

The winding of the coil around the envelope will not create any problems in the attachment of tail-fins as well as that of the gondola over the envelope, if the arrangement shown in Fig.2 is used.

**Gondola Circuit**

The circuit between the terminals "A" and "B" and lying completely within the gondola (in fact, within the cockpit) has been termed as "Gondola Circuit", and is shown in Fig.3.

The gondola circuit consists of two sub-circuits, termed as Primary gondola circuit and Secondary gondola circuit, as described ahead.
Primary Gondola Circuit

It consists of a thick small piece of a wire starting from point “A”, which is connected to a perfect Solenoid. The number of turns in the coil should be large enough to allow it to act as an electromechanical device. The turns are very closely wound to generate a large magnetic field strength. At the other end of the coil, a thick wire piece is joined, which runs to point "B", with an intermediate battery of output voltage "V" and a manually operated switch "S" provided on the control-panel in the gondola. This part of gondola-circuit is termed as the "primary gondola-circuit".

A core of highly magnetic material is put in to the left-half portion of the coil to confine and guide the magnetic field lines. It should completely lose the magnetization on switching off the external magnetic field due to which it is magnetized. Such cores include Soft-iron core, Silicon-steel core, etc. The geometry of the core is shown in Fig.4; for most part of its length (nearly up to the centre of the coil), it has a solid cylindrical structure, and for a small portion of the length beyond the centre of the coil, it has a hollow-cylindrical structure.

The geometry of the core is designed to create in small effective distance between the core and the piston (without decreasing the spring length) which results in greater magnetic force between them, thus allowing reduction in "V" for a given force. The core must be built in laminated form, with laminas arranged parallel to the magnetic field lines, to reduce the loss due to eddy-currents.

At the centre of the cross-section of the core (at the location shown in Fig.4), a compression spring is joined firmly and horizontally. The other end of the spring is connected to a piston (or plunger). When there is no current flowing in the envelope circuit, the piston lies partly inside and partly outside the coil, i.e., the solenoid of the gondola circuit. The piston is housed inside a cylinder for guiding its linear motion along the axis of the rigidly held solenoid.

The core is supported in a completely immovable position by means of several non-magnetic rigid support rods leading to perfectly rigid supports with respect to the airship. To the other end of the piston (or plunger) is connected a non-magnetic and electrically insulated rigid rod (termed as Switching Rod). To the other end of the switching rod, an electrically conducting plate is connected, as shown in Fig.3. This plate has been indicated as Switching Plate "a". To the right side of the plate "a", at a very small distance "y", there lie two other co-planar plates, as can be seen in Fig.3. These two plates have been termed as Switching Plates "b" and "c".

Secondary Gondola Circuit

The secondary gondola circuit lies between the two plates "b" and "c", and consists of the following three elements:

- An electrically operated sounding alarm.
- An external power source (a battery) of voltage output (V') volts.
- A manually operated switch (S') for manual control of the current-flow through the circuit by crew members.

The wire used to make this electrical-circuit should also be of highly conducting material and should be thick, to offer less electrical resistance, hence, to avoid any possible overheating.

The magnetic force between core and the piston should be of strength enough to accomplish the required linear movement of the piston in to the core towards its centre, when the current flows through the solenoid.

Suitable Material Combinations for Envelope and Wire of Envelope Circuit

The effectiveness and workability of the alerting system depends upon the combination of material of the envelope and of the wire of the envelope-circuit (thinner portion). Some commonly used envelope-materials and the corresponding wire-materials are listed in Table-1.

Since it is assumed that Hydrogen Gas is being used as the lifting gas, hence \( T_{SIG} = 500^\circ C \) [3]. The material-combinations recommended in Table-1 can be justified by the thermal properties of envelope-materials shown in Table-2, and the thermal and electrical properties of the wire-materials shown in Table-3.

Also, for Zinc, \( T_{SIW} = 480^\circ C \) and Electrical Conductivity = 30% of that of Copper. For Tin, \( T_{SIW} > 430^\circ C \) and Electrical Conductivity = 15% of that of Copper.
For different alloys also, listed in the last column and last row of Table-1, both the self-ignition properties and the electrical conductivity are acceptable.

**Selection of Wire Material**

As can be seen in Table-2, for most of the envelope-materials in use, $T_d < T_{SIE}$. Selection of the wire-material for a given envelope-material depends upon the condition at which the sounding of Alarm is required, as described below:

- If it is decided that Alarm should sound immediately as soon as the envelope starts degrading thermally, the materials should be used in such a combination that $T_{MW}$ is slightly lesser than $T_d$. For example, Kevlar-Tin combination, or even more safe, Kevlar-Rose’s Metal combination, Kevlar Carbon-Tin, Kevlar Carbon-Rose’s metal, PFA-Tin, PU-Rose’s Metal, Mylar-Rose’s Metal, PVC-Rose’s Metal or other alloys listed in the last column and last row of Table-1, Tedlar-Rose’s Metal, etc.
- If it is decided that the Alarm should sound when the envelope just attains the temperature $T_{SIE}$ (or $T_{ME}$ in some cases), the materials should be chosen in such a combination that

<table>
<thead>
<tr>
<th>Envelope-Material</th>
<th>Recommended Material(s) for the Wire of Envelope Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar film</td>
<td>Zinc, Tin, Rose’s Metal</td>
</tr>
<tr>
<td>Kevlar Carbon</td>
<td>Tin, Rose’s Metal</td>
</tr>
<tr>
<td>PFA (perfluoroalkoxy polymer) film or Tetrafluoroethylene-Perfluoroalkylvinylether film</td>
<td>Tin, Rose’s Metal, Cerrosafe Woods Metal</td>
</tr>
<tr>
<td>Polyurethane (PU) film</td>
<td>Tin, Rose’s Metal</td>
</tr>
<tr>
<td>Mylar film</td>
<td>Tin, Rose’s Metal</td>
</tr>
<tr>
<td>Tedlar film</td>
<td>Rose’s Metal, Woods Metal, Cerrosafe, Fields Metal, Cerrolow 136, Cerrolow 117, Cerrobase Alloy, Bi-Pb-Sn-Cd-In-T1 Alloy, Several other Cerro Alloys, Several Indium Alloys</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Envelope-Material</th>
<th>$T_d$ ($^\circ$C)</th>
<th>$T_{SIE}$ ($^\circ$C)</th>
<th>$T_{ME}$ ($^\circ$C)</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar</td>
<td>427-482</td>
<td>None</td>
<td>None</td>
<td>[7]</td>
</tr>
<tr>
<td>Kevlar Carbon</td>
<td>400</td>
<td>None</td>
<td>None</td>
<td>[8]</td>
</tr>
<tr>
<td>PFA</td>
<td>&gt; 450 (8)</td>
<td>520 (8)</td>
<td>305</td>
<td>[9]</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>&gt; 150</td>
<td>370*</td>
<td>240</td>
<td>[10][11]</td>
</tr>
<tr>
<td>Mylar</td>
<td>&gt; 150</td>
<td>425-500</td>
<td>254</td>
<td>[12][13]</td>
</tr>
<tr>
<td>PVC</td>
<td>140</td>
<td>391**</td>
<td>160</td>
<td>[14]</td>
</tr>
<tr>
<td>Tedlar</td>
<td>204</td>
<td>222***</td>
<td>190</td>
<td>[15]</td>
</tr>
</tbody>
</table>

* Decomposition Products flash at Temperature > 260°C
** Flash Ignition Temperature = 454°C [14]
*** Autogeneous Ignition Temperature

<table>
<thead>
<tr>
<th>Wire-Material</th>
<th>$T_{MW}$ ($^\circ$C)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>420</td>
<td>[16]</td>
</tr>
<tr>
<td>Tin</td>
<td>232</td>
<td>[17]</td>
</tr>
<tr>
<td>Rose’s Metal</td>
<td>96</td>
<td>[18]</td>
</tr>
<tr>
<td>Cerrosafe</td>
<td>74</td>
<td>[19]</td>
</tr>
<tr>
<td>Woods Metal</td>
<td>70</td>
<td>[20]</td>
</tr>
<tr>
<td>Fields Metal</td>
<td>62</td>
<td>[21]</td>
</tr>
<tr>
<td>Cerrolow 136</td>
<td>58</td>
<td>[22]</td>
</tr>
<tr>
<td>Cerrolow 117</td>
<td>47</td>
<td>[23]</td>
</tr>
<tr>
<td>Bi-Pb-Sn-Cd-In-T1 Alloy</td>
<td>41.5</td>
<td>[24]</td>
</tr>
</tbody>
</table>
a manner that, "\(T_{MW}\)" is slightly lesser than "\(T_{SIE}\)" or "\(T_{ME}\)", e.g., PU-Tin, Mylar-Tin combinations etc.

- If it is decided that, Alarming should occur only when the conditions have become too dangerous that if the flight is not terminated within some minutes, the leaking-out LTA-Gas (Hydrogen) can itself undergo self-ignition, the materials should be chosen in such a combination that "\(T_{MW}\)" is considerably, but not too much, lesser than "\(T_{SIE}\)", e.g., Kevlar-Zinc combination.

Since most of the commonly-used envelope-materials are very good electrical insulators, the current flowing through the envelope-circuit wire wounded over the envelope will be almost localized within the wire only, i.e., will not spread-out in the envelope-surface.

**Operation of the Alerting System**

When the pilots are ready for take-off, they should first ensure that both the switches (S) and (S') are open (Fig.3). At this stage, the switching plate "a" will be in firm electrical contact with the switching plates "b" and "c". Then, they should close the envelope-circuit by closing the switch "S". A current "I" will flow through the entire envelope circuit, and also through the solenoid of the gondola-circuit. Thus, this will result in a strong attraction between the core and the piston. Thus, there will not be attraction between the core and the piston anymore. The spring will now release the stored energy by uncompressing itself by amount "y", and the piston will be restored to its initial position, by moving towards right side by pre-determined distance "y". The switching-plate "a" will immediately come in electrical contact with the switching plates "b" and "c" due to their specifically designed geometry (shown in Fig.3).

The standard NPL Profile consist of two different semi-ellipsoidal parts joined together, with the geometry modeled by Eq.(1) and (2).

- **Frontal Ellipse:**
  \[
  \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
  \]  

- **Rear Ellipse:**
  \[
  \frac{x^2}{(\sqrt{2a})^2} + \frac{y^2}{b^2} = 1
  \]  

For NPL profile, it is known that \(L/D = 4\), \(D = 2b\) and \(L = a + \sqrt{2a} = 2.414a\).
Using standard formula of Surface-area of an ellipsoid, we have for an NPL Profile,
\[ S = 0.616L^2 \quad (3) \]

Using some standard-formulae and integral-calculus, it has been estimated that the total length of the wire in the envelope-circuit between points "A" and "B", wound around the outer surface of the envelope is \((1/(n/d))\) or \((d/n)\) times the total outer curved surface area of the envelope.

\[ l_w = \frac{1}{(n/d)} (0.616L^2) = \frac{(0.616) d L^2}{n} \quad (4) \]

Thus the total electric resistance being offered by the closed circuit composed of the envelope circuit and the primary gondola circuit (neglecting the small resistances) is given by:
\[ R = \rho \left( \frac{l_w}{A_w} \right) = \frac{(0.196) \rho L^2}{nd} \quad (5) \]

Therefore, the current in this circuit is given by:
\[ I = \frac{V}{R} = \frac{V nd}{(0.196) \rho L^2} = \frac{(5.1) V n d}{\rho L^2} \quad (6) \]

This is the energizing current for the solenoid. Hence the approximate magnetic field strength inside the sole-noid is given by (using standard formulae including Ampere’s Law):
\[ B = \mu_0 \mu_r N’ I = \frac{4\pi \times 10^{-7} \times (5.1) \mu_r N’ V n d}{\rho L^2} \]
\[ = \frac{64 \mu_r N’ V n d}{\rho L^2} \times 10^{-7} \quad (7) \]

And the approximate initial force of attraction between the core and the piston is:
\[ F = \frac{(NI)^2 \mu_0 A_c}{2 l_g^2} = \frac{13 \mu_r A_c V^2 n^2 d^2}{I_g^2 \rho L^2} \quad (8) \]

This is the very initial attractive force which acts between the core and the piston when the switching plate "a" is just at the verge of separating from switching plates "b" and "c" and the linear air-gap between the core and the piston ends is "l_g". During the motion, as the distance (air-gap) between the core and the piston continuously goes on decreasing, so the magnetic force between them also continuously goes on increasing above that given by Eqn.(8), and so is the spring force due to continuously increasing compression. But for the purpose of analysis, we will be using this value of force as constant throughout the motion of the piston, since practically, the distance moved by piston "y" is small. The piston finally comes to rest after having displacement "y", and the system attains a state of mechanical equilibrium, with the spring compressed by "y", given by:
\[ F = ky \quad (9) \]

From Eqn.(8) and (9), we have:
\[ ky = \frac{(NI)^2 \mu_0 A_c}{2 l_g^2} \rightarrow \]
\[ y = \frac{(NI)^2 \mu_0 A_c}{2 k l_g^2} = \frac{13 \mu_r A_c V^2 n^2 d^2}{I_g^2 \rho L^2 k} \quad (10) \]

Equation (10) helps in the selection of the spring or in designing the system. If the desired displacement "y" of the piston to operate the relay is pre-determined, Eqn.(10) is to be used to determine the corresponding spring stiffness "k", and hence, helps in selection of the spring from manufacturers catalogue or helps in designing the spring.

There are restrictions on the value of "y"; if it is too large, the current required in the solenoid-cum-envelope circuit for operation will be too high. So, the voltage-output "V" required will be too high. Hence, it will lead to unnecessary excessive power consumption in the maintenance of the alerting system, resulting in to low overall efficiency of the airship flight. On the other hand, "y" should not be too small either. The temperature at the surface of the envelope at any small localized site or on a bulk region could increase to high values (but below \(T_{MW}\)) due to several reasons, but in such cases, there is no need of sounding an alarm. But due to substantial temperature rise, the resistance of the wire-turns will increase, resulting in to a drop in the current "I" passing through the solenoid coil. This will cause a drop in the force of attraction between the core and the piston due to reduced intensity of magnetization in both of these elements. So, this will
cause the spring to release some of its stored strain energy by reducing its compression. Hence, the piston will move towards right somewhat out of the coil by some distance, depending upon the spring stiffness and the actual temperature rise over the envelope surface. If "\( y \)" is very small, that small displacement of the piston (due to \( T_{Ac} < T_{MW} \)) can result in to switching plate "a" coming in to electrical contact with the switching plates "b" and "c", thus causing the alarm to sound erroneously. Hence, a minimum value of "\( y \)" is to be necessarily ascertained for a given system, so that small ignorable and bearable fluctuations in the conditions of the envelope surface do not result in spurious alarms. It is recommended that "\( y \)" should not be less than 5 mm in any case, and then the spring stiffness should be calculated accordingly.

**Thermal Analysis of the Alerting System**

Since the alerting system involves use of current carrying electrical wires in close contact with the envelope surface, in which current will continuously and persistently flow, there can be a concern that it may lead to high temperature due to heat generated. However, there will also be convection of heat from the surface of the wire to the atmosphere. Hence, there is a need to carry out a thermal analysis of the system, to ensure that the alerting system itself does not heat up the airship envelope.

At the instant when flight of airship is initiated, the temperature of the wire of the envelope circuit will be same as that of the ambient atmosphere \( T_f \), and there will be no net heat-transfer between the envelope circuit and the atmosphere. When the temperature of the wire is greater than \( T_f \), the key factor governing the thermal stability of the system will be the forced convective heat transfer, as described ahead.

A continuous flow of electric current "I" is there through the envelope circuit, which results in generation of heat "\( Q_{in} \)" , and hence an initial increase in the surface temperature of the wire. But with this temperature change, the net convective heat transfer rate "\( Q_{out} \)" from wire to its surroundings will start playing a role, assuming the flight of the airship at a given constant altitude, and hence at a constant ambient temperature.

\[
Q_{in} = I^2 R = V^2 / R \tag{11}
\]

\[
Q_{out} = h A_h (\Delta T) \tag{12}
\]

Now, with continuous temperature variation of the wire, its electrical resistance changes continuously. Hence the current "I" flowing through the envelope circuit will continuously vary with time. Thus from Eqn.(11), the rate of heat generation "\( Q_{in} \)" in the wire will continuously go on varying, since "V" is constant. But with this continuous temperature change, "\( AT \)" , the temperature difference between the wire and its surroundings will vary continuously with time, and hence the Convective heat loss rate "\( Q_{out} \)" from the wire to its surroundings will continuously go on varying. At some time instant \( t_s \), these two rates ("\( Q_{in} \)" and "\( Q_{out} \)"") will become equal to each other, and a steady state will be attained, at which the temperature of the coiled wire of the envelope circuit becomes constant, and equal to \( T_s \). Since \( T_s \) remains constant, "\( R_f \)", "I", "\( Q_{in} \)", and "\( Q_{out} \)" also remain constant, and the system is now in a state of "Dynamic Thermal Equilibrium".

\( T_s \) may depend upon several factors like "V", "R", "\( h \)", "d", "\( l_w \)"., and "\( T_f \)". To ensure that "\( T_s \)" , is within the safe-limits, i.e., considerably lower than "\( T_{MW} \)", the parameters which govern its variation have to be controlled. The average convective heat transfer coefficient "\( h \)" for forced convection from the wire surface to the atmosphere is an important factor, which depends upon:

- Material of the wire
- Density and Dynamic Viscosity of the air surrounding the airship during its flight
- Orientation of the wire with respect to the oncoming flow of the air
- Prevailing flow and thermal conditions
- Nature of the surface

These key factors are generally grouped in to various dimensionless parameters, e.g., Reynolds number "Re", Nusselt number "Nu", and Prandt number "Pr".

The motion of the airship is the principal governing factor for the nature of the flow-field that the wire-turns experience during the airship flight, and not the wire-turns themselves; they face the same ambient flow field as the envelope.

The Flow Reynolds number of the airship is given by:

\[
Re = \frac{\sigma v L_c}{\mu} \tag{13}
\]
It has been seen that for several envelope profiles and their giant sizes, it is possible to maintain the Laminar or Transitional flow of the air for Reynolds number up to $2 \times 10^7$ [26-27]. Further, there is great probability of flow being laminar only at the frontal part of the airship (~ 0.1 L), before its transition to turbulent [28-29]. In general, the Reynolds number associated with turbulent flow-field should be higher than that associated with the laminar flow-field of air around the airship. Also, the Nusselt number (to which the convective heat transfer coefficient is proportionally related) for the turbulent flow-field is proportional to the higher power of Reynolds number than for the laminar flow-field [30] and the turbulent Prandtl number (= 0.85) is also greater than the laminar Prandtl number [31]. It is a well-known fact that, in general, the turbulent heat transfer coefficient is significantly higher than the laminar heat transfer coefficient, and that turbulent mixing promotes a higher convective heat transfer rate. The thermal stability of the alerting system can be checked by considering local heat transfer coefficients varying along the length of the airship due to varying flow-conditions. But, if the flow-field is assumed to be completely Laminar, and the system is found to be stable, we are on safer side, since the Turbulent flow-field will promote even better heat-transfer rates and hence will stabilize the system more effectively and safely.

While calculating the average Nusselt number for the heat transfer between the wire and the air, the "Characteristic Length" is to be taken as the Characteristic Length of the wire for the prevailing flow conditions. As the airship moves through the air, the wire-turns face the oncoming flow of air in a plane normal to the relative direction of oncoming flow of the air, which is generally along the longitudinal axis of the airship, as shown in Fig.6.

Since the size of the envelope is too large, the circumferential length of the wire in one single turn will be too large as compared to the diameter of the wire itself. Hence, the curvature effect can be neglected and this case of flow may be taken as identical to the case of a cylinder in a cross-flow. Hence, for the calculation of the Nusselt number, the "Characteristic Length" is to be taken as the diameter of the wire, for the flow of air perpendicular to the axis of wire itself.

Average Nusselt number [32] is given by:

$$ Nu = \frac{h L_{cw}}{k_u} \rightarrow Nu = \frac{h d}{k_u} \quad (14) $$

Now, Prandtl number [32] is given by:

$$ Pr = \frac{c_p \mu}{k_u} \quad (15) $$

Churchill and Bernstein [33] have recommended a single correlating equation covering conditions for which the product (RePr) > 0.2. This correlation is given by Eqn.(16) as:

$$ Nu = 0.3 + \frac{0.62 \text{Re}^{1/2} \text{Pr}^{1/3}}{[1 + (0.4/\text{Pr})^{2/3}]^{1/4}} \left[1 + \left(\frac{\text{Re}}{282000}\right)^{1/4}\right]^{1/4} \quad (16) $$

So, using Eqn.(13-16), "Re", "Pr", "Nu", and "h" can be calculated, and hence the steady-state temperature $T_s$ of the wire can be calculated, using the procedure described ahead.

The variation of the electric resistance with the temperature is assumed to be linear; hence the electrical resistance offered by the envelope circuit during the airship flight $R_f$ is given by:

$$ R_f = R \left[ 1 + \alpha \left( T_s - T_{amb} \right) \right] $$

$$ \rightarrow R_f = R \left[ 1 + \alpha \left( T_s - 288 \right) \right] \quad (17) $$

The convective heat-transfer takes place over the outer surface area of the wire, which can be estimated using Eqn(18) as:

$$ A_h = \pi d l_w \quad (18) $$

Hence the Governing Equation of the Steady-state can be written as:

$$ \text{Rate of Heat Generation in the Wire} = \text{Rate of Forced Convective Heat Loss from the Wire} $$

$$ \frac{V^2}{R_f} = h A_h (T_s - T_f) \quad (19) $$

$$ \frac{V^2}{R \left[ 1 + \alpha \left( T_s - 288 \right) \right]} = h \pi d l_w (T_s - T_f) \quad (20) $$
\( \frac{V^2}{R [1 + \alpha (T_s - 288)]} = (N_u) k_a \pi l_u (T_s - T_f) \) \hspace{1cm} (21)

Using Eqn.(4) and (5), we get:

\( \frac{V^2}{[1 + \alpha (T_s - 288)]} = 0.12 h \pi d \rho L^4 (T_s - T_f) \quad (22) \)

\( T_s \) can be estimated using Eqn. (20-22), since all other parameters are known for an alerting system designed for a given airship. The equations will be quadratic in \( T_s \), and hence there will be two possible solutions; however one of the solutions will always be below \( T_f \), which is not possible, hence it can be neglected.

**Sensitivity Analysis of Wire Thermal Parameters**

It is important to determine how changes in operational parameters of the airship affect its thermal equilibrium. This section presents results of the sensitivity of the thermal parameters to the operating altitude of the airship.

As an airship climbs to attain its design altitude, the temperature of the flight-surroundings \( T_f \) continuously decreases, almost linearly with the height. It is also clear that the temperature of the circuit wire will also continuously decrease, till it attains a steady state.

Now, with continuous temperature drop of the wire, its electrical resistance will decrease continuously. Hence the current \( I \) flowing through the envelope circuit will be continuously increasing with time. Thus from Eqn.(11), the rate of heat generation \( Q_{in}^w \) in the wire will be continuously increasing, as \( V \) is constant.

But, as this airship goes on climbing, the value of Reynolds number and Nusselt number associated with flow field as well as that of the average convective heat transfer coefficient \( h \) also goes on decreasing continuously, as shown in Table-4.

So, the wire can attain a steady state only if the rate of convective heat loss \( Q_{out}^w \) will go on increasing. Since, \( h \) is continuously decreasing and \( A_w \) is constant, so the only outcome is that \( \Delta T \) should go on increasing. Since, both \( T_f \) and the wire temperature are decreasing with climbing, therefore for temperature difference to increase, the temperatures of flight surroundings and the wire will qualitatively follow the respective profiles as shown in Fig.7.

Eventually, at some instant \( t_s \), the two rates will become equal to each other, and a steady state will be attained.

The variation of the rate of heat generation and convective heat-loss with time is shown in Fig.8a. The rate of heat loss increases much faster than the rate of heat generation. If the wire of the envelope circuit is made with a material whose electric resistance increases with the fall in temperature, rate of heat evolution and loss will follow the respective profiles as shown in Fig.8b.

The absolute increase in the value of \( T_s \) for a large increase in the value of \( V \) is too small, and can be safely neglected.

At an altitude of 10000 feet, the variation of this steady state temperature \( T_s \) with \( V \) has also been studied for the airship under consideration using Eqn.(20). It is seen that \( T_s \) varies negligibly with the variation in \( V \) from "268.20 K" at 0 volt to just "268.25 K" at 500 volt. The variation has been shown in the form of a qualitative graph in Fig.9.

**Results of Sizing and Thermal Analysis for a Sample Case**

As an example, the sizing methodology described above was applied to size the alerting system for an airship with a Hydrogen filled Kevlar envelope of length 30 m and NPL profile, operating at an altitude of 10,000 ft at a speed of 20 m/s.

Table-5 lists the key input and output parameters; it can be seen that the total mass of the alerting system for this airship is less than 7 kg, which is a very small fraction of the buoyancy force generated by the airship.

### Table-4 : Variation of Some Non-dimensional Parameters and \( h \) with Altitude

<table>
<thead>
<tr>
<th>Altitude (Feet)</th>
<th>Reynolds Number ((x 10^7))</th>
<th>Nusselt Number ((x 10^4))</th>
<th>( h ) (W/m(^2)K) ((x 10^5))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>3.57</td>
<td>3.35</td>
<td>8.15</td>
</tr>
<tr>
<td>10000</td>
<td>3.17</td>
<td>3.01</td>
<td>7.31</td>
</tr>
<tr>
<td>15000</td>
<td>2.79</td>
<td>2.68</td>
<td>6.17</td>
</tr>
<tr>
<td>20000</td>
<td>2.44</td>
<td>2.35</td>
<td>5.26</td>
</tr>
</tbody>
</table>
The methodology for carrying out the thermal analysis of the alerting system was applied to determine the steady state temperature \( T_s \) of this system, when the airship is operated at an altitude of 10,000 ft at which the ambient temperature \( T_f \) is -4.8°C (268.2 K). The key input and output parameters for this case are listed in Table-6. It can be seen that the system is thermally stable, and the temperature of the wires in the circuit stabilizes to the ambient temperature value at the steady state.

### Conclusions and Suggestions for Improvement

A safety system has been designed to alert the flight crew members when the temperature on any part of the airship envelope exceeds a pre-determined safe limit, by sounding an alarm in the cockpit. A methodology for sizing and thermal analysis of the alerting system has been developed and applied to a theoretical manned airship. The alerting system proposed in this study is seen to have a negligible mass as compared to the payload capacity of the airship. Further, it is seen that the heat generated by the circuitry of the system matches with the heat loss due to convection; hence the electrical system itself does not lead to any increase in temperature on the surface of the envelope on which it is mounted.

Some improvements can definitely be incorporated in the basic design of the alerting system, to make it lighter and more reliable. Instead of a mechanical system consisting of piston-spring arrangement, an electronic type of

### Table-5 : Key Input and Output Parameters for Sizing of the Alerting System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Input Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Envelope specific weight</td>
<td>( \sigma_E )</td>
<td>300 g/m²</td>
</tr>
<tr>
<td>Meters per turn for Envelope circuit</td>
<td>( n )</td>
<td>0.003 m</td>
</tr>
<tr>
<td>Envelope circuit wire (thin) diameter</td>
<td>( d )</td>
<td>1 mm</td>
</tr>
<tr>
<td>Envelope circuit wire (thin) material</td>
<td></td>
<td>Zinc</td>
</tr>
<tr>
<td>Resistivity of Zinc</td>
<td>( \rho_{zn} )</td>
<td>( 5.964 \times 10^{-8} ) ohm - m</td>
</tr>
<tr>
<td>Density of Zinc</td>
<td></td>
<td>7140 kg/m³</td>
</tr>
<tr>
<td>Envelope circuit wire (thick) diameter</td>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td>Envelope circuit wire (thick) length</td>
<td></td>
<td>30 m</td>
</tr>
<tr>
<td>Envelope circuit wire (thick) material</td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td>Density of Zinc</td>
<td></td>
<td>8940 kg/m³</td>
</tr>
<tr>
<td>Primary gondola circuit’s battery voltage</td>
<td>( V )</td>
<td>200 volts</td>
</tr>
<tr>
<td>Total number of turns in the solenoid</td>
<td>( N )</td>
<td>2000</td>
</tr>
<tr>
<td>Diameter of Solenoid Core</td>
<td>( d_c )</td>
<td>0.04 m</td>
</tr>
<tr>
<td>Initial air-gap between the core and the piston</td>
<td>( l_g )</td>
<td>15 mm</td>
</tr>
<tr>
<td>Final Gap between the switching plate “a” and the plane of switching plates &quot;b&quot; and &quot;c&quot;</td>
<td>( y )</td>
<td>5 mm</td>
</tr>
<tr>
<td>Key Output Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total length of envelope circuit wire (thin only)</td>
<td>( l_w )</td>
<td>184.8 m</td>
</tr>
<tr>
<td>Electric Resistance offered by the Envelope circuit</td>
<td>( R )</td>
<td>14 ohm</td>
</tr>
<tr>
<td>Envelope circuit current</td>
<td>( I )</td>
<td>14.28 A</td>
</tr>
<tr>
<td>Piston Force</td>
<td>( F )</td>
<td>0.0114 N</td>
</tr>
<tr>
<td>Spring stiffness</td>
<td>( k )</td>
<td>2.28 N/m</td>
</tr>
<tr>
<td>Mass of the alerting system</td>
<td></td>
<td>6.3 kg</td>
</tr>
</tbody>
</table>
system can be used to avoid frictional effects and overheating, and to reduce operational power consumption and eddy current losses.

Acknowledgements

This study was carried out in an internship program funded by KVPY of Indian Institute of Science, Bangalore and Department of Science and Technology, Govt. of India. The authors would like to thank their associates and well-wishers working in LTA Systems Laboratory of Department of Aerospace Engineering at Indian Institute of Technology, Bombay, and Unsteady Aerodynamics Laboratory, Department of Aerospace Engineering, Department of Mechanical Engineering, and Department of Materials Science and Engineering at Indian Institute of Technology, Kanpur for fruitful discussions and provision of study material for carrying out this work.

References


4. Material Safety Data Sheet: Cerrobase (Bismuth Based Alloy), Canada Metal, (EST) LTEE,(Eastern) Ltd.

5 Cerro Alloys (Low Melting Point Alloys) from Reade (Reade Product Catalogue).


10. Technical Bulletin-Polyurethanes and Thermal Degradation, Doc # AX-396, Centre for the Polyurethanes Industry, American Chemistry Council, 1300

Table-6: Thermal Analysis of the Alerting System While Airship is operating at an Altitude of 10,000 feet (ft)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat of air</td>
<td>$c_p$</td>
<td>$1.005 \times 10^3$ J/kgK</td>
</tr>
<tr>
<td>Thermal conductivity of air</td>
<td>$k_a$</td>
<td>0.0243 W/mK</td>
</tr>
<tr>
<td>Temperature coefficient of resistance of the wire material (Zn)</td>
<td>$\alpha_{zn}$</td>
<td>0.0037 K$^{-1}$</td>
</tr>
<tr>
<td>Melting point of envelope circuit wire material</td>
<td>$T_{MW}$</td>
<td>419.5°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key Input Parameters</th>
<th>Re</th>
<th>31.7 x 10$^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prandtl number</td>
<td>Pr</td>
<td>0.703</td>
</tr>
<tr>
<td>Nusselt number</td>
<td>Nu</td>
<td>30073</td>
</tr>
<tr>
<td>Convective heat transfer coefficient for envelope circuit wire in cross-flow</td>
<td>$h$</td>
<td>730.80 kW/m$^2$K</td>
</tr>
<tr>
<td>Steady-state temperature of the envelope circuit wire</td>
<td>$T_s$</td>
<td>-4.79°C ≈ $T_f$</td>
</tr>
</tbody>
</table>


12. Mylar® Polyester Film, Booklet for the Safe Handling, Processing, and Disposal of Mylar® Polyester Film, DuPont Teijin Films, Barley Mill Plaza, Wilmington, DE 19880-0027, Product Information


21. Roto144F Low Melt Fusible Ingot Alloy (Field’s Metal), ROTOmTeaLS, Non-Ferrous Metals and Custom Alloys.


30. Mart, S.R., McClain, S.T. and Wright, L.M., "Turbulent Convection from Deterministic Roughness Distri-


Fig. 4 Core of the Solenoid

Fig. 5 Geometry of the Standard NPL Profile [25]

Fig. 6 The Flow of the Air Perpendicular to the Plane of the Wire-turns

Fig. 7 Variation of the Temperature of Wire and "$T_f$" with Altitude

Fig. 8 Variation of Heat Generation and Heat Loss with Time
   (a) When the Wire has Positive "$\alpha$"
   (b) When the Wire has Negative "$\alpha$"

Fig. 9 Qualitative Variation of "$T_s$" with "$V$"