DEVELOPMENTS AND MODIFICATIONS OF TUNNEL VENTILATION FANS FOR EXHAUSTING HIGH TEMPERATURE GAS DURING A FIRE EMERGENCY

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ABSTRACT
A study of the operating performance of TLT axial flow tunnel ventilation fans in regards to meeting the requirement of RVS 9.261 for operating in the case of a fire emergency for 60 or 90 minutes at a temperature of 400 °C.
Also a presentation of experiences and results of a thermal finite element calculation of the essential fan components.

1 HISTORY OF EXHAUST AIR SYSTEMS
The devastating tunnel fires of the recent past demonstrate the need to improve tunnel safety systems. TLT has designed, engineered, and supplied complete tunnel ventilation systems for many years, including many systems installed in Austria. Our experience with these systems has provided us with the opportunity to study the problems of controlling the exhaust gas and smoke of tunnel fires in both new and existing facilities as well as the change in the tunnel temperature following a fire emergency. The investigation reports of tunnel fires and fire tests have shown that the main cause of death in previous tunnel fires wasn’t temperature but rather the inhalation of smoke that asphyxiated the people. In addition, considerable time was required for the temperature in the tunnel to reach a level low enough to allow emergency personnel to enter the tunnel.

In the past smoke and hot gas was exhausted through relatively small openings in the tunnel ceiling covered with either louvers or dampers. These louvers or dampers were opened either thermally or electrically in the area of or near the area of the fire. The ventilation equipment installed in this type of system was required to operate for 60 minutes at a temperature of 250 °C. The temperature rating of 250 °C was determined considering the effect of mixing the hot gas with relatively cool air drawn into the system further away from the fire. Exhausting hot gas with such a system has proven inadequate.

According to the current guidelines in Austria RVS 9.261 the tunnel ceiling openings must be much larger and are to be installed with damper systems. The openings are spaced along the tunnel length in order to be opened very close to the fire source to quickly remove the life-threatening smoke with a maximum volume. If the source of the fire is in close proximity of the exhaust fans, very high temperatures will occur at the exhaust fans because there will be little mixture of cooler air with the hot gas from the fire. Such a fire situation requires the fan design to take into consideration operation for a period of 60 or 90 minutes at a temperature of 400 °C. The requirement is defined in the Austrian RVS 9.261 (Guidelines and prescriptions for street construction) as 400 °C / 60 minutes and the German RABT (Guidelines for the equipment and operation of traffic tunnels) as 400 °C / 90 minutes.

2 TERMS OF REFERENCE OF THE STUDY
In the case of traffic tunnels with openings covered with louvers or dampers the axial flow exhaust fans are normally equipped with impeller blade modulation during operation or automatic speed control with impeller blade modulation during standstill. The fans are
selected to meet the ventilation requirements according to the characteristics of the system resistance.

The experience acquired from tunnel fires present the manufacturer of tunnel ventilation systems installed according to the previous standards with the following key questions:

1. Which materials meet the higher temperature requirements?
2. Which types of motor construction can be used in the fan-motor-unit?
3. What kind of installation and construction measures must be considered in order to control the additional strains caused by the higher design temperature requirements?
4. How can the entire system be optimized through an integration of fans and exhaust air dampers?

Our paper will concentrate on points 1 and 2. TLT has prepared a study investigating the effects on the rotating impeller mechanism while operating at the required elevated temperature. The mechanism, a technically challenging design at normal temperatures, presents additional technical considerations at 400 °C.

The study addresses the following:
- Short-time operation for 90 minutes at a maximum of 400 °C in new or existing facilities
- Long-time operation for 48 hours after a fire emergency. The time duration is the estimated length of time required for the temperature in the tunnel to reach a level low enough to allow emergency personnel to enter the tunnel.

The objective of the investigation is the verification by Finite-Element-Method of the design of axial flow ventilation fans, with impeller blade modulation during operation, exposed to increased temperatures in the event of a tunnel fire. Hot combustion gas at 400 °C is considered to be present for 60 and 90 minutes. The results can be compared with the findings of fire tests for installed fans (conducted by independent institutes).

The fire test results and Finite-Element-Method calculation reach the same conclusions.

Our study considers the stresses that occur at maximum rotational speed. The investigation includes how the dynamic heat transfer within the fan components takes place, the temperature distribution, as well as the stress distribution. Time periods are after 5 minutes, 90 minutes and 48 hours (long time operation after a fire emergency).

3 FINITE-ELEMENT-METHOD-CALCULATION

3.1 Mathematical model

For the calculation, the Finite-Element-Method (FEM) is employed by using the program system MSC/ NASTRAN. It is based on the assumption of linear geometry and material behavior. The results provide the basis for determining the correct choice of material for new facilities and what must be considered to up-grade existing exhaust fans for operation at 400 °C.

For the FEM mathematical model, the impeller of an axial flow tunnel ventilation fan with blade modulation during operation is modeled (figure 1). Exhaust fans with similar impeller designs are installed in several existing ventilation systems e.g. in the Arlberg-, Bosruck-, Gleinalm-, Tauern-, Felbertauern- and Katschberg-tunnels.

The symmetrical sector selected reflects the essential elements of the impeller design. The impeller blade of the axial fan is depicted simplistically in the geometry (flat plate), but with the correct dimensions and surface area. The details of the contact surfaces in the area of the
blade shaft bearing are exactly as designed. Here the sliding socket on the hub jacket, as well as the balls of the axial deep-groove ball bearing are to be designated with their contact surfaces to the adjacent parts. The mathematical network is constructed from 8 nodal hexaeder elements. Only the stiffeners in the impeller are replicated with shell elements. The inside system border is formed by the shaft of the drive motor of the fan-motor-unit (figure 2).

![figure 1: FEM-model overview](image1)  ![figure 2: FEM net](image2)

3.2 Assumptions and boundary conditions

Our FEM calculations are based upon the following assumptions and boundary conditions:

The model is fixed in all directions within the area of the motor shaft. Beside the definition of the thermal boundary conditions for the calculation of the transient temperature field the centrifugal force is considered as a load case corresponding to a blade tip speed of 164 m s\(^{-1}\). The study is based on the assumption of linear thermal conduction. The material characteristic values are accepted as constant for the considered temperature range.

With the known formulas of thermodynamics for fan blades in the hot gas stream, the heat transmission co-efficient \(\alpha = 325 \text{ W m}^{-2} \text{ K}^{-1}\) for the turbulent flow is obtained from the relative inflow velocity of the blade vane at the maximal operating point. For such surfaces, which are in direct contact with the hot combustion gases (blade and impeller outer jacket), this heat transmission co-efficient is used for the temperature field calculation (forced convection). The temperature of the hot combustion gas is a constant 400 °C. The surface of the impeller side panels are cooled by the flow of outside air at a constant temperature of 40 °C (figure 3). The starting temperature of the entire structure is 40 °C at the point in time \(t = 0\) s. The surfaces in the inside of the structure are expected as adiabatic. This means that the influence of radiant heat transfer between individual components is not considered in the analysis. This simplification is appropriate because the impeller jacket includes insulation installed inside the impeller, which shields the components from the hot surface.
3.3 Calculations

The transient temperature calculation is considered over a period of 48 hours. The temperature distributions are recorded at various points in time and the displacements resulting from the elevated temperatures are used for a stress analysis. These stresses are superimposed to the stresses resulting from the centrifugal force from operation.

3.4 Results

3.4.1 Transient temperature fields

After 1 minute the surfaces in direct contact with the hot gas have attained the temperature of 400 °C. The heat conduction to the inside of the impeller occurs very slowly as the conditions illustrate after 5 or after 90 minutes (figures 4 and 5). The calculation method is also used to predict the stress of the fan components during a shutdown of the tunnel over a period of 48 hours after a fire emergency (figure 6). The long term calculation does not consider any reduction of the exhaust gas medium temperature.
3.4.2 Stress

For the evaluation of the stress, the temperature influence at various points in time is considered. High stress occurs where high temperature gradients are present. This is the case in the impeller outer jacket and in both the impellers’ cover plates where a very high gradient is present at a very small radial distance. These plates are cooled by 40 °C seal air.

The maximum local stress is approx. 600 N mm⁻² in the impeller outer jacket.

The maximum stress of the main load carrying components is approx. 200 N mm⁻² (figure 7) after 90 minutes.

Finally, the stress resulting from the increased temperature after 90 minutes is superimposed with the centrifugal force. The influence of the centrifugal force on the material stress is negligible in the event of fire (figure 8). Please note that even after 48 hours the additional influence of temperature on stress compared to the 90 minutes values is very minimal.

4 SUMMARY

4.1 Fundamentals

Tunnel axial fans with impeller blade modulation during operation can be built to meet the requirement of 400 °C operation for a period of 90 minutes if they are designed with the proper operating systems and constructed with the proper materials.

4.2 Consequences for new facilities

In the case of new facilities impeller blades fabricated from nodular cast iron should be utilized. This type of blade construction has a proven record of operation in hundreds of induced draft installations in the power station industry. Heat transfer from the impeller blade to the motor shaft and into the adjacent components of the motor has not been experienced within the short-time operation of 90 minutes and is not expected for longer operating times under conditions of a fire emergency.

Heat-resistant materials are not necessary for the motor shaft. In addition, extremely large bearing clearances are not required.

Supplementary to our thermal investigations of the fan, we have been informed of a new development in the design of motors for use in tunnel exhaust air fans designed for operation up to 400 °C for the duration of 90 minutes. Motors have been developed with a totally enclosed construction (protective class IP 54/55), surface-cooled, which are certified for operation at 400 °C for the duration of 120 minutes. The motors do not require separate cooling. The appropriate certificates have been submitted by the manufacturers.
4.3 Consequences for existing facilities

Fan rotors with aluminum impeller blades designed for operation at 250 °C (in individual cases up to 350 °C) cannot be employed at 400 °C. Aluminum impeller blades represent a high safety risk for exhaust air fans in the event of fire.

The fan impeller design with nodular cast iron blades designed for new facilities will have considerably larger component masses and moments of inertia. If such an impeller were considered for replacement in an existing facility it would require replacement of the entire fan assembly. In order to be able to use as much of the existing fan assembly as possible, impellers with similar dimensional relationships as the existing facilities must be used. Choosing the blade material to replace nodular cast iron is especially important due to the influence the blade weight has on the operating characteristics of the fan. A sensible mechanical and economic choice would be Titanium impeller blades. Optimizing the number of blades, profile thickness and the resulting lighter impeller construction will result in dimensional relationships and center of gravity distances similar to the initial installation.

The existing motors can be used for the 400 °C specification for the period of 90 minutes by modifying the cooling system and with simple changes to the fan housing.

Through these manageable revisions to the existing installations shutdown of the traffic flow in the tunnel would be minimized. It is likely that a shutdown of the tunnel need only take place for several hours at a time.

4.4 Consequences of a long time, 48 hour, shutdown of the tunnel in the event of a fire in new facilities

Utilizing the newly developed motors designed for high temperature operation in connection with an additional external ventilation system, as well as a sealed fan hub with internal insulation, longer motor operating time can be realized at 400 °C medium temperature. In addition, a longer operation time during cooling down of the tunnel after a fire emergency can be achieved with this design concept for new facilities.

An additional advantage also exists. Even if the external ventilation system fails the original specification of 400 °C for a period of 60 or 90 minutes could be achieved.

From our perspective this concept should be taken into consideration as a further enhancement of tunnel safety in the event of a fire emergency.

5 FINAL REMARKS

The study results demonstrate that tunnel safety can be enhanced through appropriate measures.

It is our opinion that up-grading existing facilities with equipment meeting the new standards is imperative. The cost for refurbishment of existing equipment required to meet these new standards can be minimized by selecting the respective materials for the application.

In the case of new facilities we recommend the use of exhaust fans designed for operation at 400 °C with nodular cast iron blades and motors designed for operation in hot gas.

Development of TLT exhaust fans capable of operating at 400 °C has been completed as far as possible. The focus of future research and development activities will be the development of other system components such as dampers.

p.s.: Interested parties may contact TLT to get a colored copy of the pictures.