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A VAPOR GENERATOR FOR TRANSONIC FLOW VISUALIZATION

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SUMMARY

A vapor generator system has been developed for use in the NASA Langley Transonic Dynamics Tunnel (TDT). Propylene glycol is used as the vapor material. The vapor generator system was evaluated in a laboratory setting and then used in the TDT as part of a laser light sheet flow visualization system. The vapor generator provided satisfactory seeding of the air flow with visible condensate particles, "smoke", for tests ranging from low subsonic through transonic speeds and for tunnel total pressures from atmospheric pressure down to less than 0.1 atmospheric pressure.

INTRODUCTION

A vapor generator has been developed for use in the NASA Langley Transonic Dynamics Tunnel (TDT). The generator is designed to generate particles by condensation of a vapor injected into the airflow upstream of a wind tunnel model to aid in visualizing the flow field characteristics. The TDT is a continuous flow, single return wind tunnel with a 16-ft. square test section (reference 1). The tunnel is equipped to use either air or R-12 (dichlorodifluoromethane) as the test medium at tunnel total pressures which vary from near vacuum to atmospheric pressure.

The requirement for the number of particles generated per unit time for flow visualization increases with air speed. The range in test airspeed for the TDT is from near zero velocity to Mach 1.2. There are four basic requirements for the vapor generator. First, a sufficient number of particles must be present in the flow to be visible at transonic speeds. Second, a vapor material must be used which is non-toxic and non-carcinogenic. Third, the vapor material must not contaminate or damage the test facility. Finally, the size of the particles must be controlled. This is especially important for laser velocimeter, LV, measurements where the particle size should be of the order of one micron. This last requirement is often difficult to achieve.

In this paper the vapor generator system is described and the principal of operation is explained. This is followed by an example of an application of the system in the TDT.

VAPOR GENERATOR SYSTEM

The vapor generator system, as shown in the schematic of figure 1, is composed of a pressure supply, a pressure regulator and several metering and shutoff valves, the reservoir tank containing the material to be vaporized, tubing, the vaporizer, and a heated hose to transfer the vaporized material to the tunnel insertion point. The schematic also shows a tube supplying mixing jet gas which was used in the laboratory setup but not in the tunnel test. Propylene glycol (PG) was selected and is used as the vapor material because it is non-toxic and non-carcinogenic and does not contaminate or damage the test facility. Several of the properties and characteristics of propylene glycol are listed in Table I.

Reservoir Tank System

The pressurized reservoir tank which contains the liquid propylene glycol is shown in figure 2 along with the pressure regulator, a fluid flow measurement device, and several valves used to control flow rate and facilitate refilling. The tank has a five gallon capacity.

Vaporizer Assembly

The vaporizer is shown in the photograph of figure 3 prior to wiring of the heating elements and connection of the copper tubing. The casing or housing is an aluminum cylinder with end plates. The housing is 8 inches long by 5.75 inches in diameter. There are twelve cartridge heating elements, six inserted from each end of the casing as shown in figure 4. The heating elements are within straight tubes which traverse the housing from end to end. Copper tubing wound around the straight tubes forms a cylindrical coil around each of the six pairs of heating elements. One of the final steps in the assembly process was to fill the empty space in the housing with cast zinc which functions as a thermal mass. To reduce heat loss during operation the vaporizer is covered with an insulating blanket as shown in figure 5.

Heating Elements and Temperature Control.- One of the heating elements is shown in figure 3 outside of the vaporizer case. The 525 watt heating elements are 0.625 inch diameter by 3.75 inch long. Power to the heating elements is provided through a temperature control system shown in the schematic of figure 6. The temperature controller located in the control room allows the operator to adjust the vaporizer system temperature as needed. Normal operation has been to keep the vaporizer temperature at approximately 425 °F. The vaporizer temperature is sensed by an iron constantan thermocouple located inside the vaporizer case adjacent to the cast zinc thermal mass. The power relay is located in the tunnel plenum chamber adjacent to the vaporizer. For the setup used, as defined by figure 6, the relay supplied 3 phase, 440 Volt power to the vaporizer heating elements as called for by the controller. The wiring configuration for the twelve heating elements in the vaporizer, using the 3 phase, 440 Volt source, is shown as the top schematic in figure 7. The remaining four schematics in figure 7 show how the same twelve heating elements would be wired if the source voltage were different, as listed to the right of each schematic. On the schematics the heating elements are represented by the open circles. The wiring connectors for six of the heating elements are at one end of the vaporizer case and the wiring connectors for the remaining six heating elements are at the opposite end of the case.

Copper Tubing Connections.- The 0.25 inch diameter copper tubing inside the case is coiled in cylindrical form around each of the six heating element pairs for efficient heating of the vapor material flowing through the tubing. The copper tubing for each of the six cylindrical coils enters the case at one end, forms the cylindrical coil around the straight tube containing a pair of heating elements, and then exits at the opposite end of the casing. In figure 2 the copper tubing external to the case is shown prior to connections being made between coils. The six coils of copper tubing could be connected in various ways. For the unit described herein the tubing was connected so that the liquid propylene glycol flows through a single coil around a pair of heating elements on its first pass through the case. The tubing then is connected to a "T" fitting allowing the vapor to expand and flow through a pair of coils on the second pass through the case. The tubing connections then allow the vapor to expand further and pass through three coils on the third and last pass through the case. These three tubes are then interconnected to a 1/2 inch diameter exit tube.

Transfer Hose

A 15 ft long, 1/2 inch diameter heated hose, that is available commercially, is used to transfer the vaporized material from the vaporizer to near the tunnel insertion point . The heated hose has an internal temperature controller to maintain a fixed temperature of 425 °F. For most tunnel model installations a short length (less than 12 inches) of unheated and uninsulated tubing is also needed to bring the vapor from the end of the heated hose to the desired insertion point for the model being tested.

PRINCIPAL OF OPERATION

The formation of a condensed vapor "smoke" can be explained with the aid of figure 8 which presents the equilibrium vapor pressure curve for propylene glycol as a function of temperature and the partial pressure of the propylene glycol vapor. The information in figure 8 assumes the tunnel gas "test medium" is air at one atmosphere pressure (2116 psf) and a temperature of 100 °F. The partial pressure of propylene glycol is based on the molar fraction of propylene glycol in the propylene glycol and air mixture being considered. If pure propylene glycol vapor is being injected into the tunnel, then its partial pressure is one atmosphere or 2116 psf. If the vapor being introduced into the tunnel is a mixture of propylene glycol where the molar fraction represented by propylene glycol was one-half, then the partial pressure of the propylene glycol vapor would be 1058 psf.

At temperature and partial pressure conditions above the equilibrium vapor pressure curve of figure 8 the propylene glycol mixture will be a vapor. Also shown on figure 8 is the supersaturation curve which, for any given temperature, is at a partial pressure three times greater than that of the equilibrium vapor pressure curve (Saturation ratio, S=3). In the region between the equilibrium vapor pressure curve and the supersaturation curve the vapor can condense. However, there is insufficient energy to create a new interface surface so condensation will occur only on pre-existing particles such as dust or aerosol droplets. At temperature and partial pressure conditions below the supersaturation curve (S>3), spontaneous nucleation can occur allowing the vapor to condensate to small droplets or particles which are visible as "smoke". The largest number of particles are formed, and therefore the optical density of the "smoke" is greatest when the injected vapor is mixed rapidly with the cooler tunnel gas to quickly reach the region of spontaneous nucleation.

Point A on figure 8 represents pure propylene glycol vapor (partial pressure = 2116 psfa) at the vaporizer temperature of 425 °F. Note that the vaporizer temperature is approximately 55 °F hotter than the condensation temperature defined by the equilibrium vapor pressure curve. This allows for some heat loss in the unheated portion of tubing delivering the vapor to the desired discharge point in the tunnel. Point B represents conditions at the point of vapor injection into the tunnel stream based on the assumption that the vapor has cooled to 375 °F by heat losses through the tube walls. At the point of injection into the tunnel the propylene glycol vapor mixes with the cooler tunnel gas (air) with two effects. It dilutes the vapor (reduces the partial pressure of the propylene glycol), and it reduces its temperature. The curve, which originates at point B and passes through points C and D, represents the cooling and partial pressure reduction experienced by the initially pure propylene glycol vapor as it mixes with the cooler tunnel gas. Spontaneous nucleation or "smoke" generation will occur only after the vapor has been diluted and cooled past point D on the curve.

When only pure liquid propylene glycol is admitted to the vaporizer, the vapor pressure of the boiling liquid helps propel the vapor to the discharge point. This operation tends to be unstable since the vapor flow rate varies directly with the vaporizer pressure, and the boiling rate tends to drop with increased pressure. This results in the vapor being discharged in a nonuniform manner as a series of puffs. The introduction of a small quantity of the same gas as the test medium (air or R-12) eliminates this puffing by providing a more continuous flow through the vaporizer.

The quantity of this dilution gas flow is not critical and it is usually set near the minimum flow rate which eliminates the puffing. Point A' on figure 8 represents the case where diluent gas (air) is mixed with the propylene glycol before entering the vaporizer such that equal molar quantities of propylene glycol and air are at the vaporizer temperature of 425 °F (the partial pressure of the propylene glycol is 1058 psfa). Condensation of the vapor on the walls of the injection tubing could occur if the vapor mixture cooled to less than 330 °F before being injected into the tunnel. Point B' assumes that the propylene glycol and air mixture has cooled only to about 340 °F before injection into the tunnel airstream. Mixing with the tunnel gas produces the curve of temperature with partial pressure which originates at point B' and passes through points C' and D'. As stated previously, spontaneous nucleation or "smoke" generation will occur only after the vapor has been diluted and cooled past point D' on the curve.

Tests were conducted in a laboratory setting where propylene glycol vapor was discharged into still air, with and without an additional flow (jet) of air impinging on the vapor flow. The tests were performed to determine the effect of rapid cooling and mixing on resultant particle sizes and numbers. Typical particle size distributions with and without added cooling air flow from an air jet are presented in figure 9. When the vapor is discharged directly into still air with no added cooling air flow, the particle size distribution is centered on a diameter of about 4.7 micrometers with about 450 particles in that size category. When a jet of cooling air is impinged on the vapor discharge, the size distribution is shifted to a larger number of smaller particles. The distribution with mixing is centered on a diameter of about 1.0 micrometers with about 850 particles in that size category. For tunnel operations where the vapor is being introduced directly into the flow, sufficiently rapid mixing and cooling of the vapor may result, dependent on tunnel airspeed and on the location and configuration of the vapor discharge nozzle, to make the introduction of additional cooling gas unnecessary.

The range of temperatures and flow rates that were determined to be optimum in the still atmosphere laboratory environment are listed in Table II. Only the range of optimum temperature is relatively small. The fluid flow rate may be increased as necessary and the dilution gas adjusted accordingly. The flow rates listed in the table were determined using calibrated flow meters in the lab setup. The use of calibrated flow meters is not necessary for a permanent installation. Locations of metering valves which may be calibrated at initial installation are shown in figure 1.

APPLICATION

The vapor generator system was utilized as part of a laser light sheet flow visualization system to study the leading edge vortex of a semi-span clipped delta wing model in the TDT. Figure 10 is a photograph taken during the wind tunnel test. The wing leading edge sweep was 50.5 degrees and the wing semi-span measured 27.85 inches. A single discharge nozzle for the propylene glycol vapor was located at the wing root near the leading edge flow stagnation point. This resulted in condensed propylene glycol vapor being entrained in the vortex along the leading edge of the model where it could be illuminated by the laser light sheet. The model is at 15 degrees angle of attack, the Mach number is 0.92, and the dynamic pressure is 51.3 psf. The light sheet is oriented streamwise and located at the 50% span station. The light sheet illuminates the leading edge vortex and the vortex burst location (the point at which the illuminated area increases). The vapor generator system was successfully used for this test series with both air and R-12 test mediums and at tunnel total pressures from atmospheric pressure down to 1/12 atmosphere.

CONCLUDING REMARKS

A vapor generator for transonic flow visualization has been developed and utilized in the Transonic Dynamics Tunnel. The propylene glycol vapor used is non-toxic and non-carcinogenic, and the vapor does not contaminate or damage the test facility. The vapor generator provides sufficient particles for laser vapor screen transonic flow visualization. The vapor generator was successfully used in air and R-12 from atmospheric pressure down to 1/12 atmosphere.

REFERENCES

1. Reed, Wilmer H., III: Aeroelasticity Matters: Some Reflections on Two Decades of Testing in the NASA Langley Transonic Dynamics Tunnel. NASA TM-83210, 1981.

Table I.- Propylene Glycol Properties and Characteristics.

Item	Value
Molecular Weight	76.1
Apparent Specific Gravity at 20/20° C	1.0381
Boiling Point at 760 mm. Hg.	(187.3° C) 369° F
Vapor Pressure at 20° C	< 0.1 mm. Hg
Freezing Point	-60° C
Viscosity at 20° C	60.5 cp
Heat of Vaporization at 1 atm.	296 BTU/lb
Flash Point	214° F
Solubility in Water	Complete

Table II.- Optimum System Conditions From Laboratory Tests.

System Parameter	Allowable Range
Vapor Generator Case Temperature	420°F to 440°F
Heated Hose Temperature	425°F (fixed)
Reservoir Tank Pressure	35 psi
Propylene Glycol Flow Rate	up to 2.5 gph
Dilution Gas Flow Rate	0.1 to 1.0 cfm
Mixing Gas Flow Rate	0.75 to 3.0 cfm

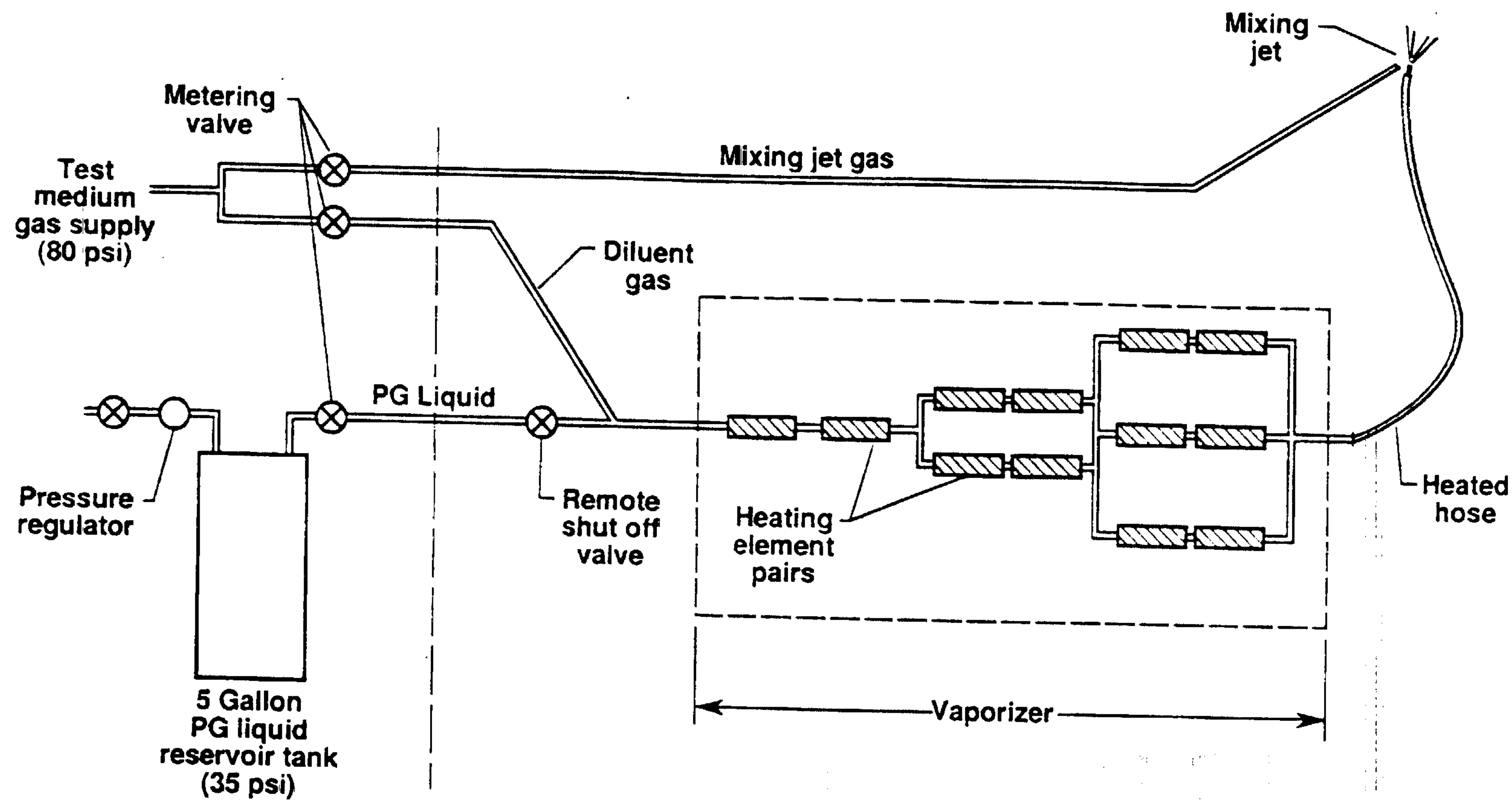

Figure 1. - Schematic of the vapor generator system.

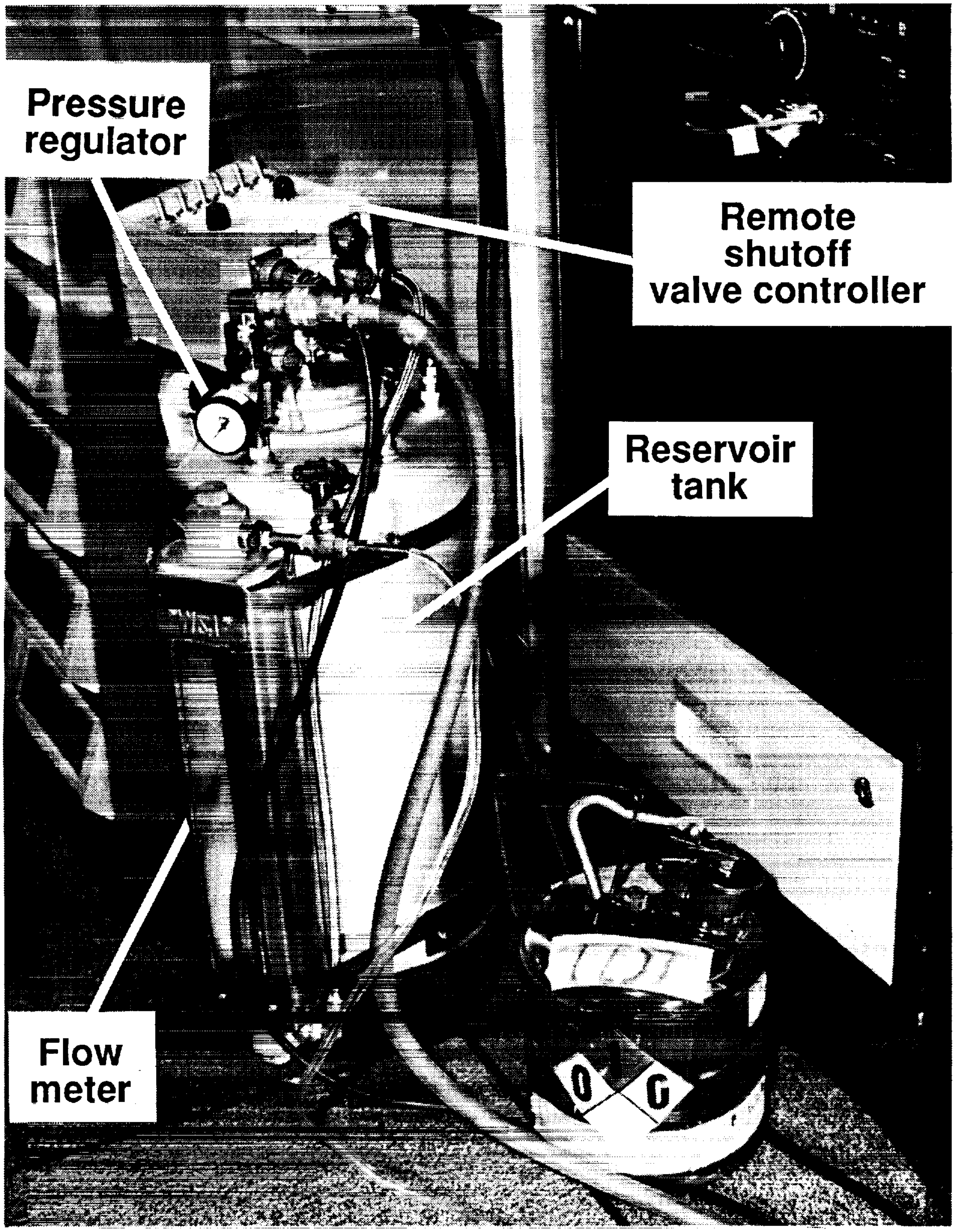

Figure 2. - Reservoir tank system.

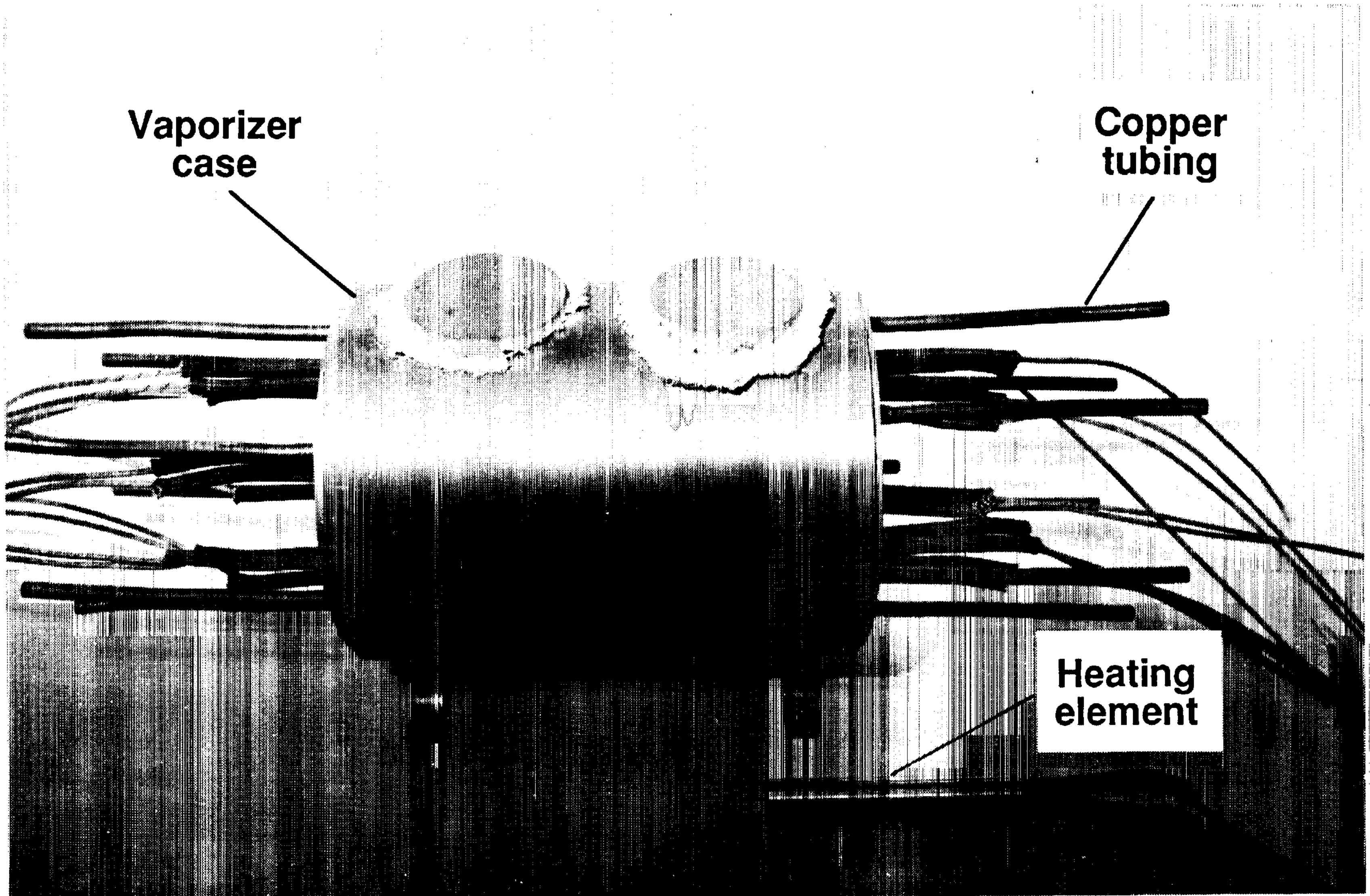

Figure 3. - Vaporizer prior to the connection of the heating elements and copper tubing.

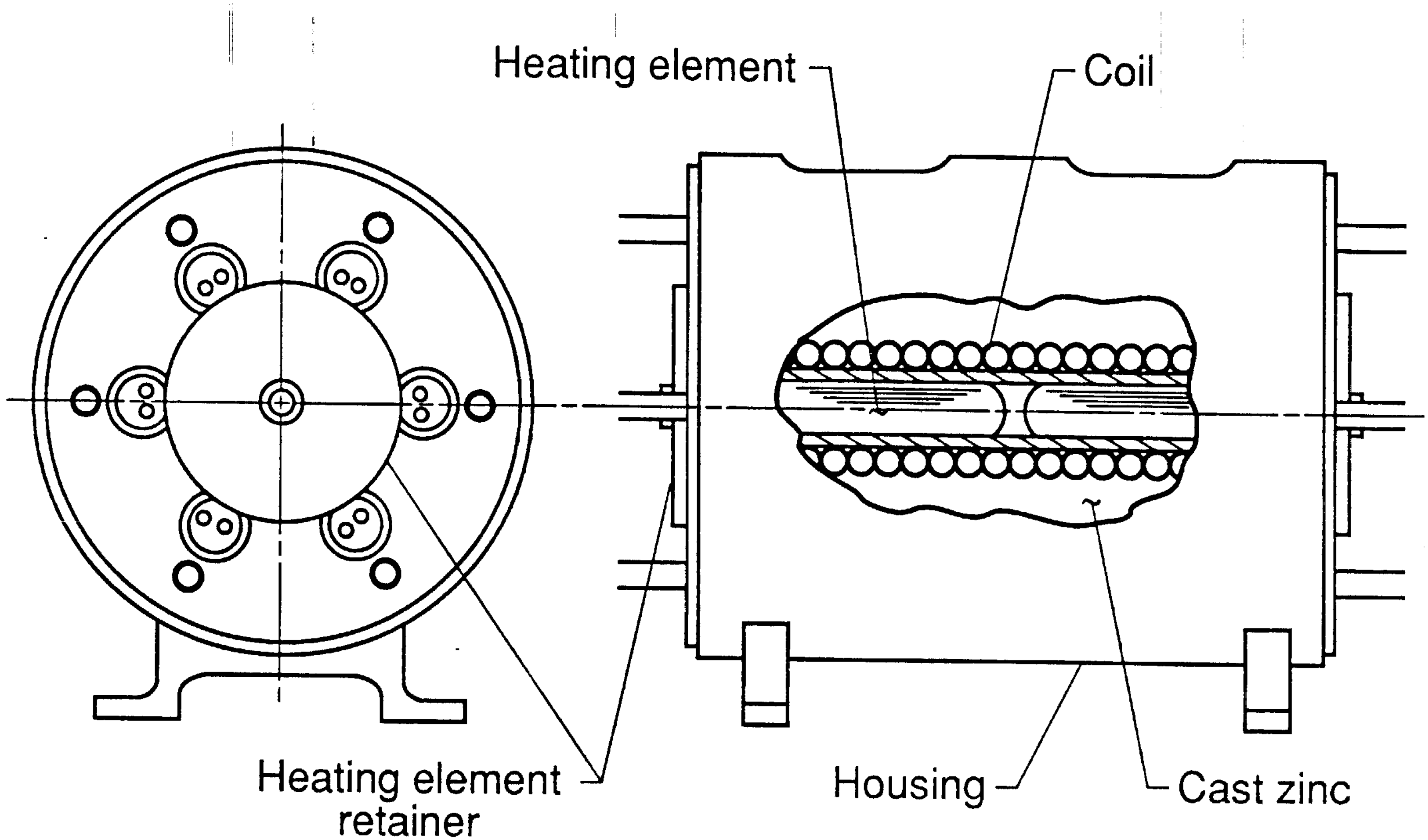

Figure 4. - Sketch of the vaporizer.

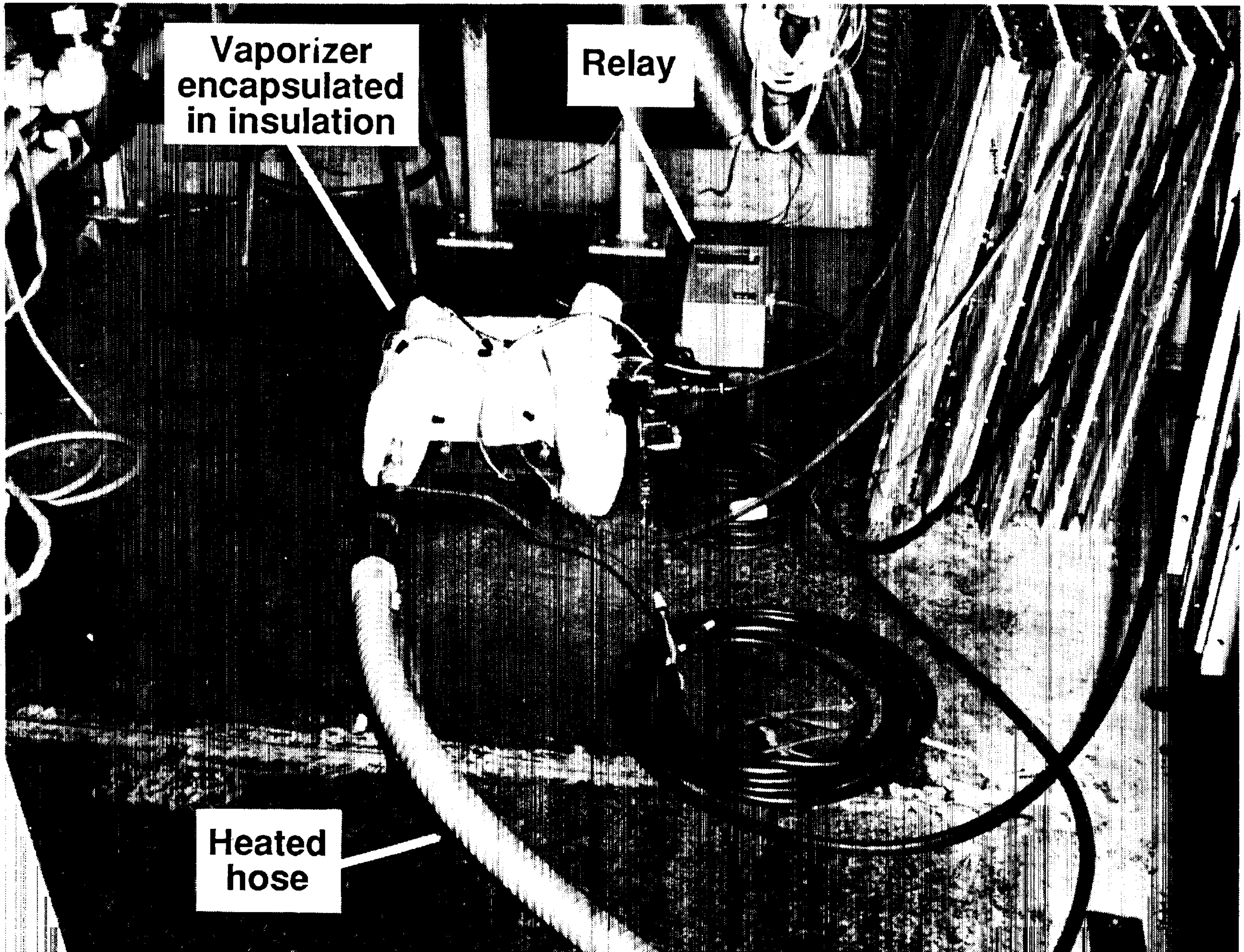

Figure 5. - Photograph of the vaporizer and related components.

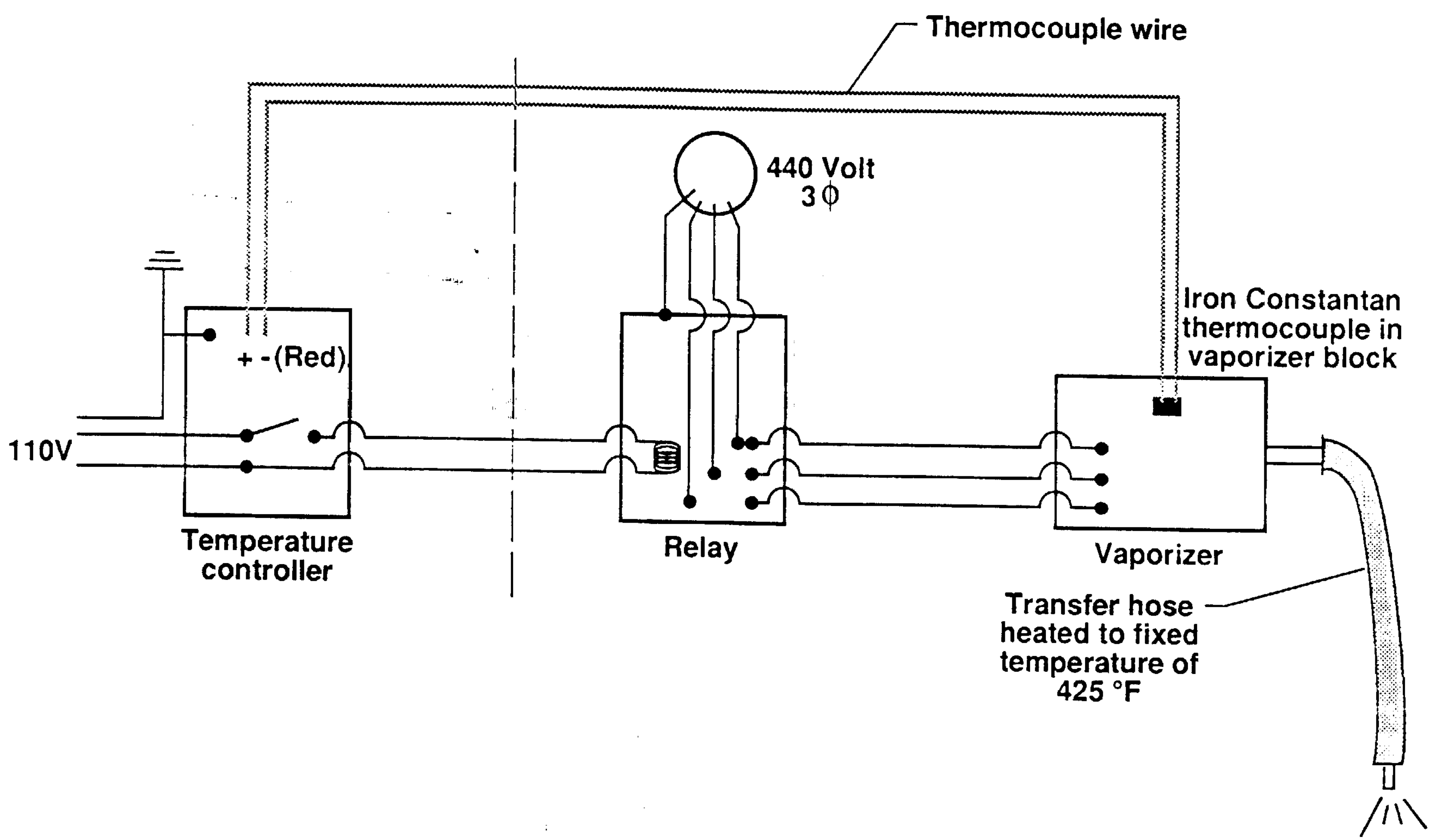

Figure 6. - Schematic of the electrical system.

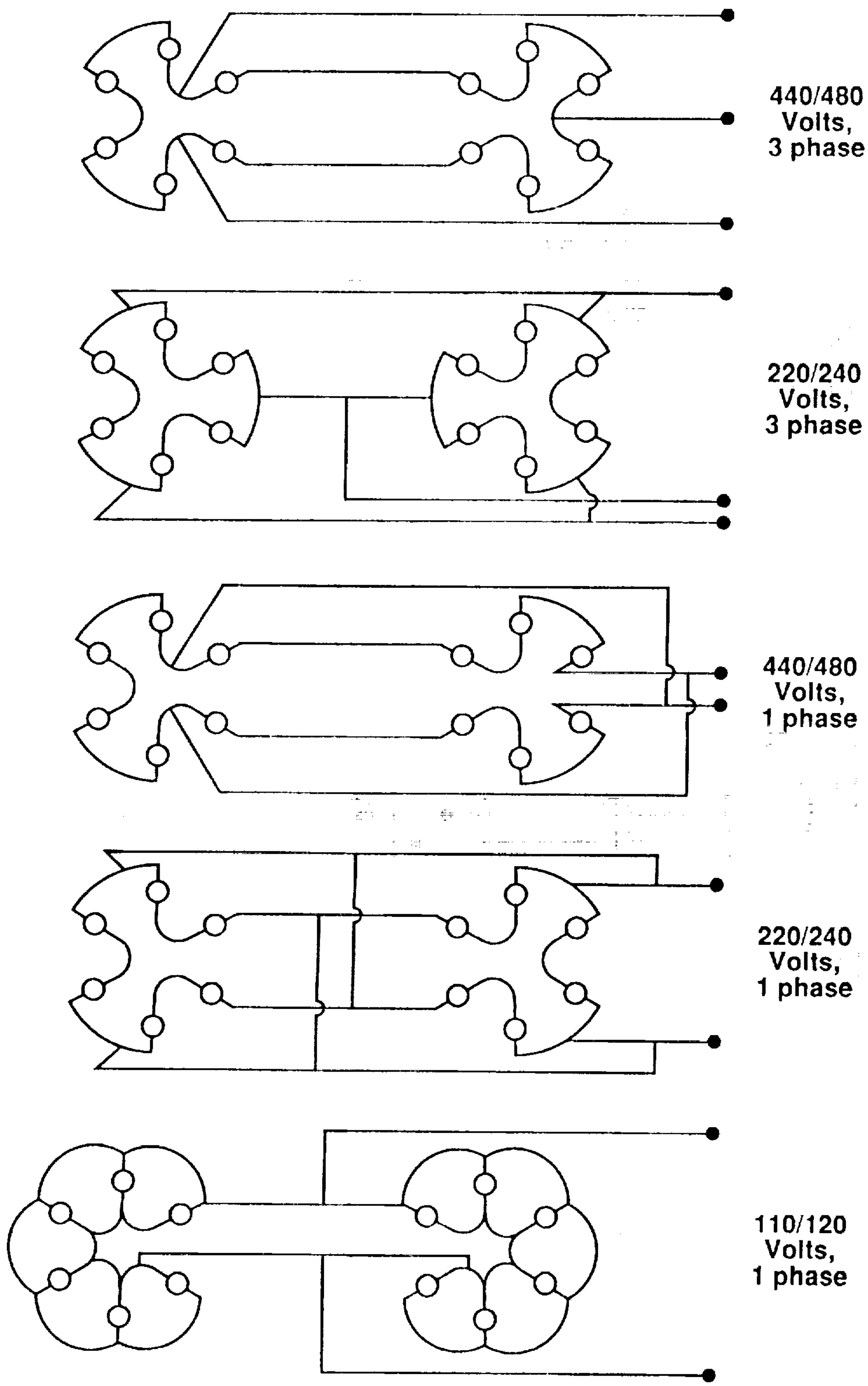

Figure 7. - Wiring configurations for different voltage sources.

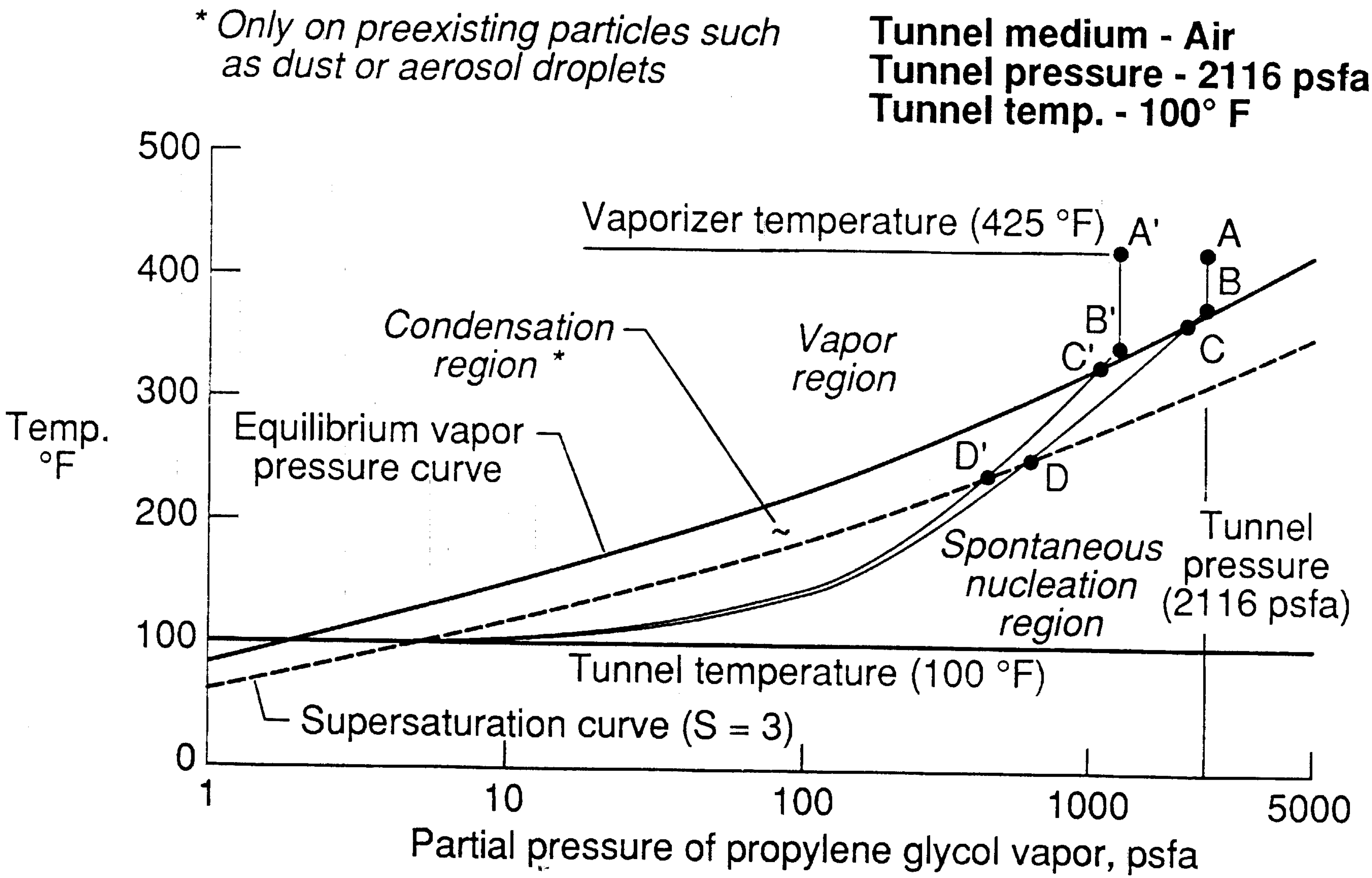

Figure 8. - Formation of propylene glycol smoke.

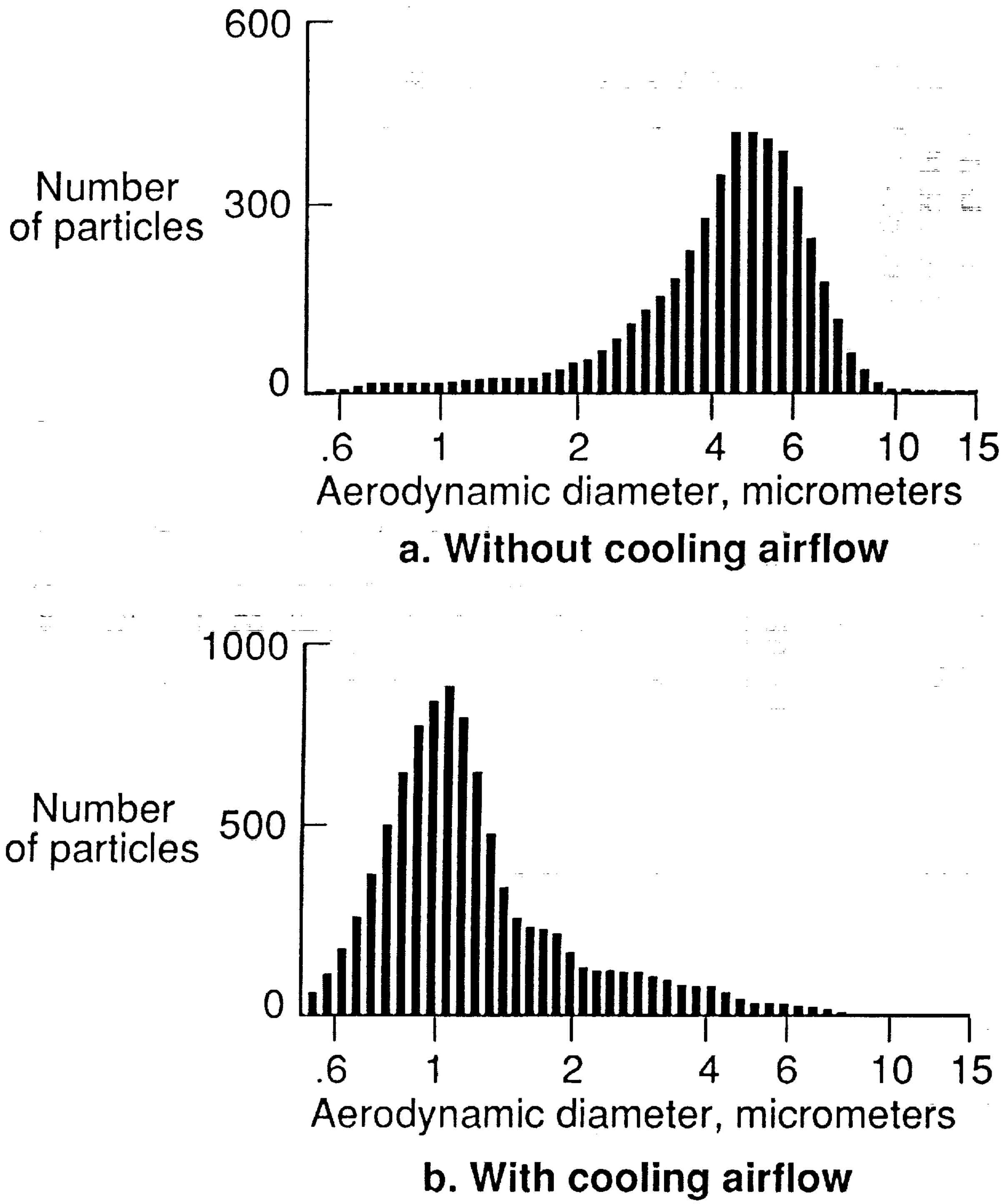

Figure 9. - Effect of cooling air flow on particle size.

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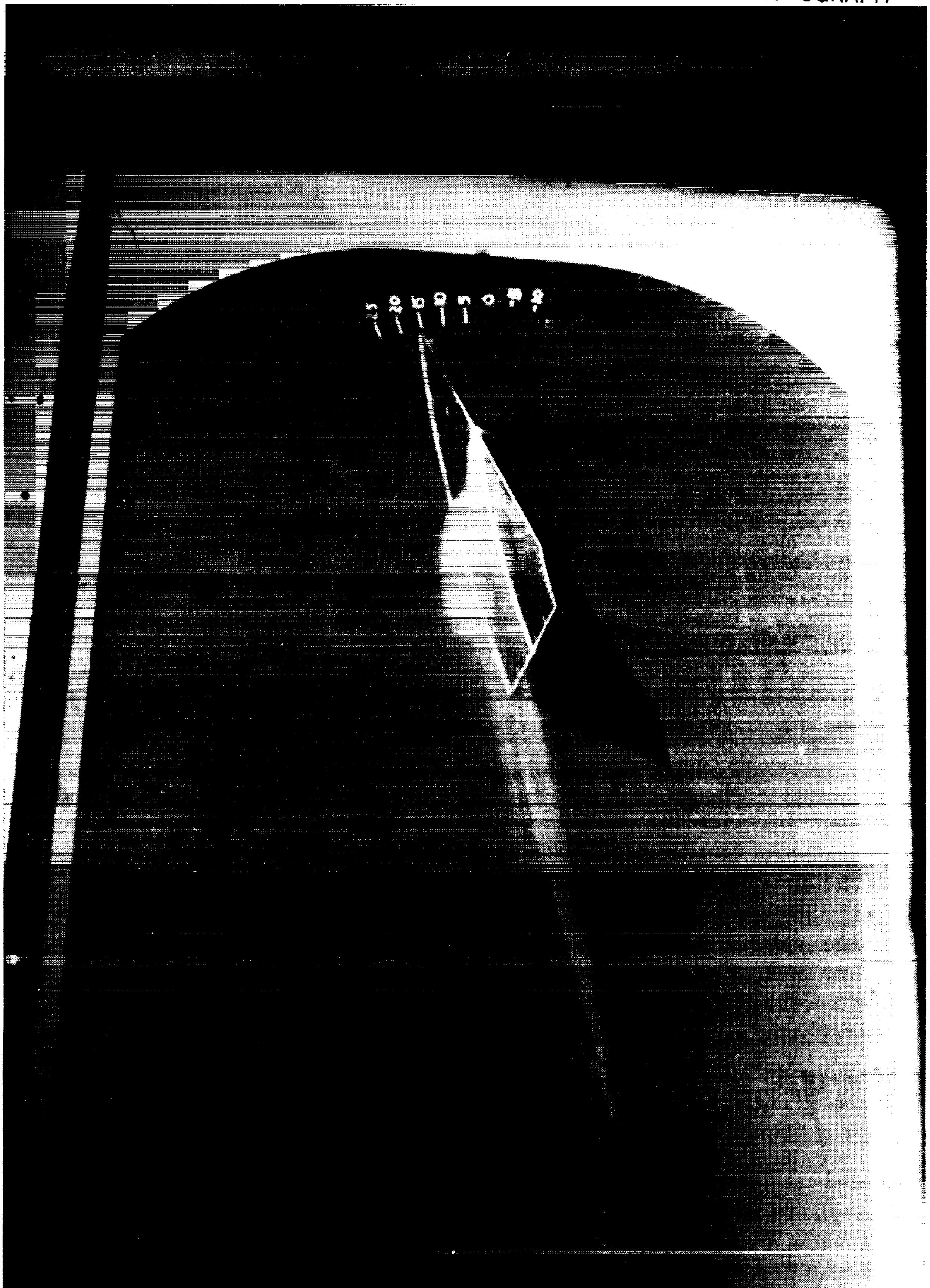

Figure 10. - Photograph of model during leading edge vortex study.

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16. Abstract

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