

A Simple Method to Assess the Quenching Effectiveness of Fire Suppressants

C.T. Avedisian^{*}, C. Presser[‡], J. Stiehl^{*}, and R.E. Cavicchi[‡]

^{*} Sibley School of Mechanical and Aerospace Engineering
Cornell University
Ithaca, NY 14853-7501

[‡] Chemical Science and Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8360

Corresponding Author

Cary Presser
NIST
100 Bureau Dr., Stop 8360
Gaithersburg, MD 20899-8360

301-975-2612
cpresser@nist.gov

Abstract

A screening concept is suggested for evaluating the effectiveness of fluids to thermally suppress fires. It is based on measuring a fluid's ability to inhibit (or quench) the temperature rise of a material that is rapidly heated. The experimental design is similar to the transient hot wire technique in which the evolution of the average material temperature is recorded for a given input power, and internal temperature gradients in the material are minimized. A gold wire (100 μm long and 5 μm diameter) is used as the surface which heats the fluid. The wire temperature response due to a power pulse provides a measure of the effectiveness of the fluid to suppress thermally the temperature

increase. The results indicate that the “quenching effectiveness”, $QE = \frac{T_{\max} - T_{\infty}}{T_{\max,ref} - T_{\infty}}$,

correlates with the ratio of the fluid thermal conductivity to that of the wire, k_{fluid}/k_{solid} , using different Nusselt numbers (representing both conduction and natural convection) for the liquids or gases. The concept developed here could be included in a more comprehensive screening protocol, which would assess the thermal potential of candidate fire suppressants.

keywords: fire suppressant; pulse heating; extinction; transient heating; thermal conductivity; quenching effectiveness; suppression effectiveness

Introduction

A fire suppressant derives its effectiveness by extinguishing a burning surface through chemical, thermal, and physical mechanisms. Previous work [1] is notable for the articulation of thermal, physical, and chemical effects on flame extinction especially for gaseous agents (e.g., trifluoromethane, CF_3H , and bromo-trifluoromethane, CF_3Br) [2]. The ability to separate suppressant mechanisms when using an actual fire configuration in testing is difficult. Experimental screening methods generally rank agents according to the integrated physical, thermal, and chemical effects that lead to flame extinction [3]. The efficacy of new fire suppressants is facilitated by screening methods that segregate the mechanisms involved in the processes leading to flame extinction. A testing protocol that decouples these effects could provide a clearer understanding of the mechanisms associated with suppressant of a particular fire. Linteris et al. [4] noted that the flame configuration itself could influence the relative suppression effectiveness. At the same time, useful information can be obtained even if the results are unique to that configuration, and indeed, this is the case for standardized screening protocols (e.g., counterflow burner [e.g., 5], cup burner screens [e.g., 6], and turbulent spray flames [e.g., 7]).

Several studies have attempted to isolate individual mechanisms of suppression. For example, Pitts et al. [8] ranked suppressants according to their thermophysical properties (i.e., the latent heat of vaporization, heat capacity, and boiling point were used to estimate the total absorbed heat). Agents were selected according to this ranking to test in various screens for their suppression effectiveness. Lentati and Chelliah [9] used a numerical model to unmask physical, thermal, and chemical effects in a counterflow

configuration in which monodispersed water droplets were introduced into the flow field. A follow-up experimental study [10] indicated that water mists were effective suppressants due to its thermal behavior (as effective as CF_3Br), and that a strategy of mixing thermal components with chemical components may lead to the development of superior fire suppressants.

Presented is a concept to evaluate the heat transfer properties of fire suppressant fluids, through the interaction of a cold fluid with a hot surface. The experimental approach is based on the pulse heating of a solid material - a metal in the proposed configuration - that is submerged in a test fluid, and monitoring the temperature change of the solid during the power pulse. This configuration is relevant to a re-ignitable hot surface in fire scenarios, as had been investigated by Hamins et al. [3]. We did not consider the condition where vaporization would occur, but the approach is amenable to the characterization of vaporization effects. Vaporization of the fluid would be manifested as an inflection point at the start of nucleation and an increased rate of temperature rise thereafter [11].

Experimental Arrangement

Figure 1 presents a schematic of the experimental arrangement. In general, a programmed power pulse is imposed on a small diameter metal wire that forms one leg of a bridge circuit. The wire is immersed in the fluid and supported only by its electrical wire-bond connection at either end. During the pulse, the wire electrical resistance is monitored with a fast-transient data acquisition system. The hot wire serves as both an energy source to impart a precise and controllable amount of thermal energy to the

surrounding fluid and a temperature sensor through the relationship of electrical resistance with temperature of the wire material from a separate calibration. The fluid that best restrains the temperature change of the wire during the heating process is considered to be the most thermally effective agent.

The gold wire is 5 μm in diameter (D) and 2.1 mm in length (L)¹. This choice of physical dimensions and material for the wire simplifies the analysis of the results by satisfying the so-called 'lumped-capacitance approximation' which is characterized by a small Biot number ($Bi = hD/k_{solid} < 0.1$, where h is the convection heat transfer coefficient and k_{solid} is the wire thermal conductivity). The measured room temperature resistance of this wire is $R_{ho} = 2.58 \Omega$ (at 295 K). An adjustable resistor (R_p) is used to balance the wire resistor R_h on the opposite leg of the bridge prior to heating the gold wire, as shown in Fig. 1, and we take $R_l = 2.29 \Omega$. The bridge is mounted on a 3M² Model 309 breadboard which facilitates changing bridge resistances, as needed. The wire is mounted across corner pads of a 40 pin dual-in-line package (DIP, Aries Model 40-6553-18 high-temperature test socket, max: 523 K). The DIP is incorporated directly into the bridge circuit (see Fig. 1).

A voltage pulse (V_{in}) is imposed across the bridge of time duration Δt by an Agilent Model 8114A pulse generator. The output voltage (V_{out}) is monitored by a LeCroy WaveRunner Model 44xi 5Gs/s digital oscilloscope through a LeCroy Model AP033 differential amplifier and the voltage is converted to wire resistance with the equations of bridge circuitry [12]. Data files are stored directly on the oscilloscope and

¹Relevant properties of gold (at 300 K) are the following: solid density (19,300 $\text{kg}\cdot\text{m}^{-3}$); specific heat (129 $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$); thermal conductivity (318 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$).

²Certain commercial equipment or materials are identified in this publication to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for this purpose.

later transferred to a personal computer for analysis. A calibration of wire resistance is used to obtain the average temperature of the wire during the power pulse.

A 50 μs pulse duration was selected and fixed throughout the study to provide a valid basis for comparing different fluids. The input voltage to the bridge was adjusted so that the average wire temperature in air was about 560 K at the end of the 50 μs pulse. The choice of a 50 μs pulse mitigated thermal shock effects and potential damage associated with repeated thermal stressing of the wire. The pulse time was short enough to reduce the onset of natural convection and prevent vaporization of the liquids investigated (i.e., significant superheating can be sustained with pulse heating). The additional conditions of $V_{in} = 2.9$ V and bridge resistance $R_l = 2.29$ Ω ensure that the wire temperature is far from the melting point of gold (1337 K) at the end of the pulse, and an output signal of sufficient magnitude is obtained to differentiate between the examined fluids. The short-duration pulsing, which is accomplished with the aforementioned power electronics, is sufficient to assume a fast-response assessment.

The power (p) generated by the wire at any instant of time (t) is determined from the bridge equations as

$$p = V_{in}(t)^2 \frac{R_h(t)}{[R_l + R_h(t)]^2} \quad 1$$

Accounting for the change of R_h with heating, the power input during the 50 μs pulse duration is between 0.7 W and 0.8 W.

Before a new fluid is examined, the wire is carefully cleaned by gentle flushing with methanol and baking in an oven for several hours. Power pulses are then imposed on the wire in air (parameters specified above) to ensure that the resulting evolution of temperature and average wire temperature after 50 μs is repeatable in air (achieving a maximum wire temperature $T_{max} = 560 \text{ K}$), as noted above. Small systematic variations of input power are sometimes required to adjust the bridge impedance and V_{in} to achieve T_{max} for air. This effect may be due to annealing of the wire associated with repeated pulsing that varied slightly the electrical conditions. By adjusting the input electrical parameters, using the peak temperature achieved in air after 50 μs , it was possible to ensure a uniform starting condition for examining the thermal response of the wire with each new fluid.

Both liquids and gases were examined. Measurements with liquids were carried out by placing a drop of the test fluid on the DIP recess to submerge the wire, and then powering the wire typically at a frequency of 10 Hz. Gases were studied by placing the DIP with bonded gold wire into a 2.54 cm diameter test tube, which was closed with a two-holed rubber stopper to provide a sealed containment for the gas. Glass tubes, which passed through the stopper holes, were connected to ball valves to control the gas flow through the test tube. The bonded wires, which were connected to the DIP and attached to the bridge circuit, were threaded out of the test tube and sealed by press fitting the wires against the rubber stopper. Before each experiment, the gas was allowed to flow through the test tube for several minutes. The ball valves were then closed quickly to seal the gas inside the test tube after which the wire was heated in the aforementioned manner.

The variation of gold wire resistance with temperature was calibrated by slowly heating the wire in a Thermolyne Model 48000 computer-controlled furnace while monitoring the temperature of the DIP with an Omega Model KMQXL-010U-12 (250 μm diameter, sheathed, ungrounded, K-type) thermocouple placed in the space between the DIP and test socket. The thermocouple time response, as specified by the manufacturer, was estimated to be 0.5 s in water (0.8 s in air) at a level of confidence of 95 %. The expanded uncertainty for the temperature was estimated to be 7.9 K, including the Type B uncertainty of 3.1 K³, and represented the major source of uncertainty in the measurement. The resistance was monitored during heating by an HP Model 3457 digital multimeter interfaced with a personal computer. Control of the calibration process was accomplished with a LABView program. Room temperature was recorded with an HP Model 2804A quartz probe, which served as the standard for calibration of the thermocouple.

The resistance calibration of the gold wire with varying oven temperature was found to have a hysteresis between the heating and cooling (having lower resistance values) portions of the calibration, which was attributed to annealing of the wire while cycling the temperature. A linear fit to the data was then used to correlate the wire resistance with the oven temperature (T_{TC}) as

$$R_h = a + b T_{TC} \quad 2$$

³ Estimation of the measurement uncertainty is determined from statistical analysis of a series of replicated measurements (referred to as Type A evaluation of uncertainty) and from means other than statistical analysis (e.g., manufacturer estimates, referred to as Type B evaluation of uncertainty) [13].

where $a = -0.00331 \Omega$ and $b = 0.00877 \Omega/K$. The wire temperature (T) is determined from Eq. 6 of Ref. [12], using the wire resistance obtained from the calibration, and $a = R_{ho} [1 - \theta_R T_s]$, $b = R_{ho} \theta_R$, and $\theta_R = 0.003394$.

In Table 1, the first seven fluids are fire suppressant-related agents. The remaining ten fluids are not suppressants but are nonetheless included for completeness in the context of a larger class of fluids. Solid aerosol powders, water mists, and particle/fluid suspensions fire suppressants are not considered here. Issues arise regarding the influence of a temperature gradient imposed by the hot wire (i.e., which could impart a thermophoretic force to the particles and artificially influence their proximity to the wire) on suspended particles.

Results and Discussion

The experimental results are presented in terms of a simple lumped thermal model for heat transfer between the wire and fluid for constant internal generation of heat and fixed ambient temperature. Assuming constant properties, a constant input power, and single-phase heat transfer, it can be shown that at the end of a power pulse (of duration t_{max}) [14]

$$\theta_{max} = \frac{\bar{p}}{\xi} \left(1 - e^{-\xi \tau_{max}} \right) \quad 3$$

where $\theta_{max} = \frac{T_{max} - T_{\infty}}{T_{\infty}}$, $\tau_{max} = \frac{\alpha_{solid} t_{max}}{D^2}$, $\bar{p} = \frac{4p}{\pi k_{solid} L T_{\infty}}$, and

$$\xi = 4Nu \frac{k_{fluid}}{k_{solid}}. \quad 4$$

where θ_{max} is the nondimensional temperature difference at T_{max} , T_∞ is the ambient fluid temperature, τ_{max} is the nondimensional time at t_{max} , α is the thermal diffusivity, k is the thermal conductivity, and \bar{p} is the nondimensional power (p). The variable ξ is important for assessing the thermal behavior of fire suppressant since it depends on the heat transfer mechanism between the fluid and wire (through the Nusselt number, Nu), and the ratio of fluid to solid thermal conductivity. The Nusselt number is altered according to whether the flow between the fluid and wire is laminar or turbulent, and mechanism of heat transfer is conductive or convective.

Table 1 presents values of ξ along with the quenching effectiveness (QE), which is defined as the ratio of the maximum temperature relative to that of water at the end of the 50 μ s pulse, $QE \equiv \theta_{max}/\theta_{max,ref}$ where $\theta_{max,ref} = \frac{T_{max,ref} - T_\infty}{T_\infty}$ and $T_{max,ref}$ (at 50 μ s) = 339 K for $T_\infty \approx 295$ K (the laboratory environment) as measured for water. The reported uncertainties for QE and ξ are based on relatively small Type A uncertainties for the electronic components, which supports the small variability in the measurements observed for each individual fluid (see the values of R_h in Table 1), and enabling us to confidently list the values of QE in the ascending order given in Table 1. The major component of uncertainty lies with the thermocouple Type B values (as provided by the manufacturer) that was used for the calibration, however, since the reported temperatures were based on the linear fit through the calibration data, the relative effect on the results given in Table 1 will be negligible. The term QE is a measure of a fluid's ability to

suppress the temperature change of a surface suddenly to an ambience at a different temperature. It may be larger or smaller than unity depending on the value of $\theta_{max,ref}$. Among a class of fluids the most effective suppressant from a thermal standpoint has the smallest QE and highest ξ . On this basis, water is the most thermally effective.

Comparing the fluids in Table 1, all of the liquids have a smaller value of QE than the gases (given in italics). Among the gases in Table 1, helium is the most effective (having the smallest value) principally because of its relatively high thermal conductivity. The value of QE for the hydrofluoroethane $C_4F_7OH_3$ is somewhat smaller than $C_5F_9OH_3$ and, thus, $C_4F_7OH_3$ may be slightly preferable to $C_5F_9OH_3$ for fire suppression. The perfluorocarbon C_6F_{14} has a slightly larger value of QE than the two hydrofluoroethanes. The alcohols (not relevant to fire suppression but interesting nonetheless to view their ranking) have higher values of QE than the alkanes.

Although gases appear to be less thermally effective than liquids, it is well known that certain gases are extremely effective fire suppressants. The case of CF_3Br is especially interesting in the context of the present study. It has the largest value of QE (smallest value of ξ) compared to all of the fluids examined and, so, would be considered a less thermally effective suppressant than the other fluids listed in Table 1. However, CF_3Br is known to be an extremely effective suppressant. The reason attributed to chemical effects in which Br recombines catalytically H or OH radicals to reduce the radical pool and lead to flame extinction [1,2]. This example illustrates that thermal nor chemical considerations alone dictate the effectiveness of a fluid for fire suppression (indeed, flammable liquids with no relevance to fire suppression have higher values of QE (lower values of ξ) than fluids which are known to be effective suppressants, as

indicated in Table 1). It will certainly be true that fluids which are effective both chemically and thermally (i.e., having lower values of QE and higher values of ξ) will be preferable to fluids with the opposite thermal characteristics.

Equations 3 and 4 suggest that θ_{max} should correlate with k_{fluid}/k_{solid} for a given value of Nu and \bar{p} . Figure 2 presents the variation of θ_{max} with ratio of fluid to solid thermal conductivity for the fluids listed in Table 1. The correlations for gases and liquids are segregated for a given \bar{p} - a consequence of the large difference in liquid and gas properties which produce $Nu_{liquid} > Nu_{gas}$. A regression analysis was used to fit the data using Nu and \bar{p} as parameters. The results indicate that the input power is almost the same for the gases and liquids examined (i.e., $\bar{p}_{gas} = 0.00354$ and $\bar{p}_{liquid} = 0.00353$), while values of $Nu_{gas} = 0.456$ and $Nu_{liquid} = 4.252$ provide the best match to the measurements. The gas Nusselt number is remarkably close to the conduction limit, $Nu = 0.36$ [14], while the value of Nu_{liquid} suggests that heating in the liquids may have induced some level of convection. The lines drawn in Fig. 2 are based on Eq. 3, using the stated values for the nondimensional power and Nusselt number. The close agreement of Eq. 3 with the data shown in Fig. 2 suggests that the simplified model represents reasonably well the experimental measurements.

Summary

A screening concept, based on the transient hot-wire technique, is presented to evaluate the thermal potential of a liquid or gaseous fire suppressant to restrain the temperature change associated with interaction of a cold fluid with a comparatively hot (or burning) surface. A nondimensional parameter based on inhibiting either the

temporal change in wire surface temperature or the maximum temperature reached at the end of the power pulse is used to rank different chemical agents. The liquids as a group appear to be better thermally effective suppressants than the gases. Water is considered the 'best' thermally effective suppressant (surface coolant) from among the fluids examined. A lumped thermal system was found to reproduce the measurements with appropriate values of the Nusselt number.

Nomenclature

Bi	Biot number ($= h \cdot D \cdot k_{solid}^{-1}$)
D	wire diameter (m)
h	convection heat transfer coefficient ($W \cdot K^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	wire length (m)
Nu	Nusselt number (Eq. 9.34 of Ref. [14])
p	power (W)
\bar{p}	nondimensional power
QE	quenching effectiveness based on the temperature derivative
R_h	wire resistance (Ω)
R_{ho}	wire resistance at room temperature (Ω)
R_p	adjustable resistor (Ω)
R_l	bridge resistances (Ω)
t	time (s)
T	wire temperature (K)
T_{TC}	oven temperature (K)
T_*	ambient fluid temperature (K)
V_{in}	input voltage to bridge (V)
V_{out}	bridge output voltage (V)

Greek

α	thermal diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$)
Δt	time duration (s)
θ	nondimensional temperature difference
θ_R	thermal coefficient of resistivity (K^{-1})
ξ	suppression effectiveness parameter base on T_{max}
τ	nondimensional time

Subscript

<i>fluid</i>	referenced to the suppression agent
<i>gas</i>	gaseous agent
<i>liquid</i>	liquid agent
<i>max</i>	referenced to the value near end of pulse (near $t = 50 \mu\text{s}$)
<i>ref</i>	referenced to the value of water
<i>solid</i>	referenced to the gold wire

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Table 1: Computed values of quenching effectiveness (QE) and other relevant fluid properties (fluids in bold are known fire suppressants and in italics are gases; bracketed numbers are values for water). The term ξ was determined iteratively from Eq. 3. For water as the reference, $\theta_{max,ref} = 0.149 \pm 4 \cdot 10^{-3}$ and $k_{ref} = 0.638 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The reported uncertainties are calculated as $k_c u_c$, where k_c is the coverage factor (= 2) and u_c is the combined standard uncertainty.

	Chemical Name	Chemical Formula	$R_{h,max}$ [Ω]	QE [$\equiv \theta_{max}/\theta_{max,ref}$]	k/k_{ref}	ξ
1	water	H ₂ O	$2.97 \pm 4 \cdot 10^{-3}$	$1.00 \pm 4 \cdot 10^{-2}$	1.00 ^c	$2.50 \cdot 10^{-2} \pm 7 \cdot 10^{-4}$
2	60 % potassium acetate/water	KC ₂ H ₃ O ₂ /H ₂ O	$3.09 \pm 4 \cdot 10^{-3}$	$1.31 \pm 5 \cdot 10^{-2}$	0.80 ^d	$1.90 \cdot 10^{-2} \pm 4 \cdot 10^{-4}$
3	methanol	CH ₄ O	$3.45 \pm 5 \cdot 10^{-3}$	$2.25 \pm 7 \cdot 10^{-2}$	0.30 ^e	$1.01 \cdot 10^{-2} \pm 1 \cdot 10^{-4}$
4	ethanol	C ₂ H ₆ O	$3.53 \pm 5 \cdot 10^{-3}$	$2.46 \pm 8 \cdot 10^{-2}$	0.24 ^e	$8.90 \cdot 10^{-3} \pm 1 \cdot 10^{-4}$
5	1-pentanol	C ₅ H ₁₂ O	$3.56 \pm 5 \cdot 10^{-3}$	$2.55 \pm 8 \cdot 10^{-2}$	0.22 ^e	$8.50 \cdot 10^{-3} \pm 1 \cdot 10^{-4}$
6	1-propanol	C ₃ H ₈ O	$3.58 \pm 5 \cdot 10^{-3}$	$2.58 \pm 8 \cdot 10^{-2}$	0.23 ^e	$8.36 \cdot 10^{-3} \pm 1 \cdot 10^{-4}$
7	n-decane	C ₁₀ H ₂₂	$3.74 \pm 6 \cdot 10^{-3}$	$3.00 \pm 9 \cdot 10^{-2}$	0.18 ^e	$6.50 \cdot 10^{-3} \pm 9 \cdot 10^{-5}$
8	n-nonane	C ₉ H ₂₀	$3.76 \pm 6 \cdot 10^{-3}$	$3.06 \pm 9 \cdot 10^{-2}$	0.17 ^e	$6.30 \cdot 10^{-3} \pm 8 \cdot 10^{-5}$
9	n-hexane	C ₆ H ₁₄	$3.80 \pm 6 \cdot 10^{-3}$	$3.17 \pm 9 \cdot 10^{-2}$	0.15 ^e	$5.90 \cdot 10^{-3} \pm 8 \cdot 10^{-5}$
10	1-methoxyheptafluoropropane (HFE7000)^a	C ₄ F ₇ OH ₃	$4.25 \pm 7 \cdot 10^{-3}$	$4.32 \pm 1 \cdot 10^{-1}$	0.09 ^c	$2.76 \cdot 10^{-3} \pm 4 \cdot 10^{-5}$
11	methoxy-nonafluorobutane (HFE7100)^a	C ₅ F ₉ OH ₃	$4.26 \pm 7 \cdot 10^{-3}$	$4.36 \pm 1 \cdot 10^{-1}$	0.08 ^c	$2.60 \cdot 10^{-3} \pm 4 \cdot 10^{-5}$
12	perfluoro-n-hexane (FC-72)^b	C ₆ F ₁₄	$4.27 \pm 7 \cdot 10^{-3}$	$4.38 \pm 1 \cdot 10^{-1}$	0.09 ^f	$2.52 \cdot 10^{-3} \pm 4 \cdot 10^{-5}$
13	<i>helium</i>	He	$4.62 \pm 7 \cdot 10^{-3}$	$5.28 \pm 2 \cdot 10^{-1}$	0.30 ^g	$1.35 \cdot 10^{-3} \pm 3 \cdot 10^{-5}$
14	<i>air</i>	-	$4.84 \pm 8 \cdot 10^{-3}$	$5.86 \pm 2 \cdot 10^{-1}$	0.06 ^g	$4.00 \cdot 10^{-4} \pm 1 \cdot 10^{-5}$
15	1,1,1,2,2-pentafluoroethane (HFC-125)	C ₂ HF ₅	$4.84 \pm 8 \cdot 10^{-3}$	$5.86 \pm 2 \cdot 10^{-1}$	0.05 ^h	$4.00 \cdot 10^{-4} \pm 1 \cdot 10^{-5}$
16	bromotrifluoromethane (Halon 1301)	CF ₃ Br	$4.91 \pm 8 \cdot 10^{-3}$	$6.03 \pm 2 \cdot 10^{-1}$	0.03 ⁱ	$1.00 \cdot 10^{-4} \pm 9 \cdot 10^{-6}$

^a3M™ Novec™ Engineered Fluid

^b3M™ Fluorinert™ Electronic Liquid

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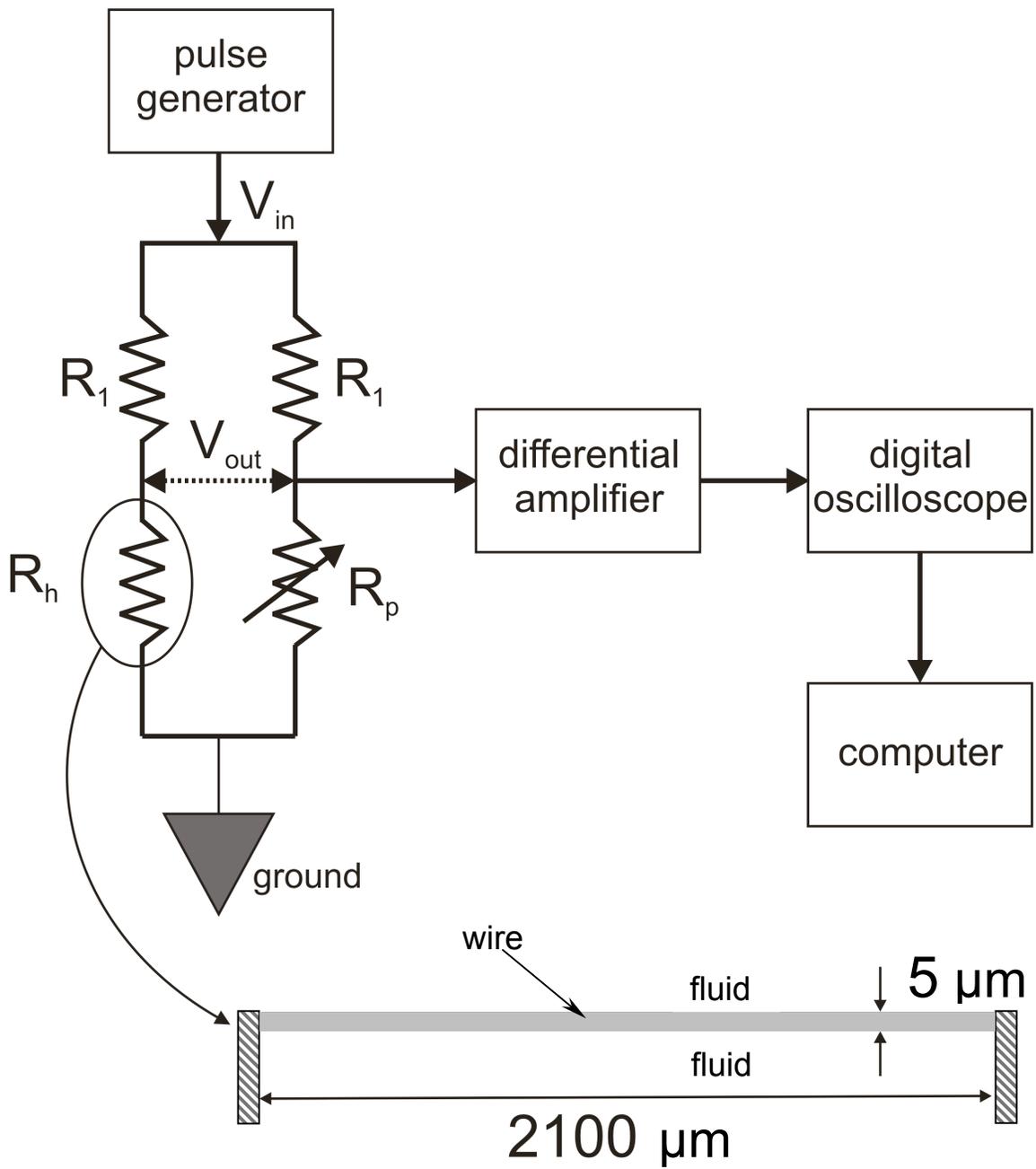


Figure 1. Schematic of the experimental arrangement.

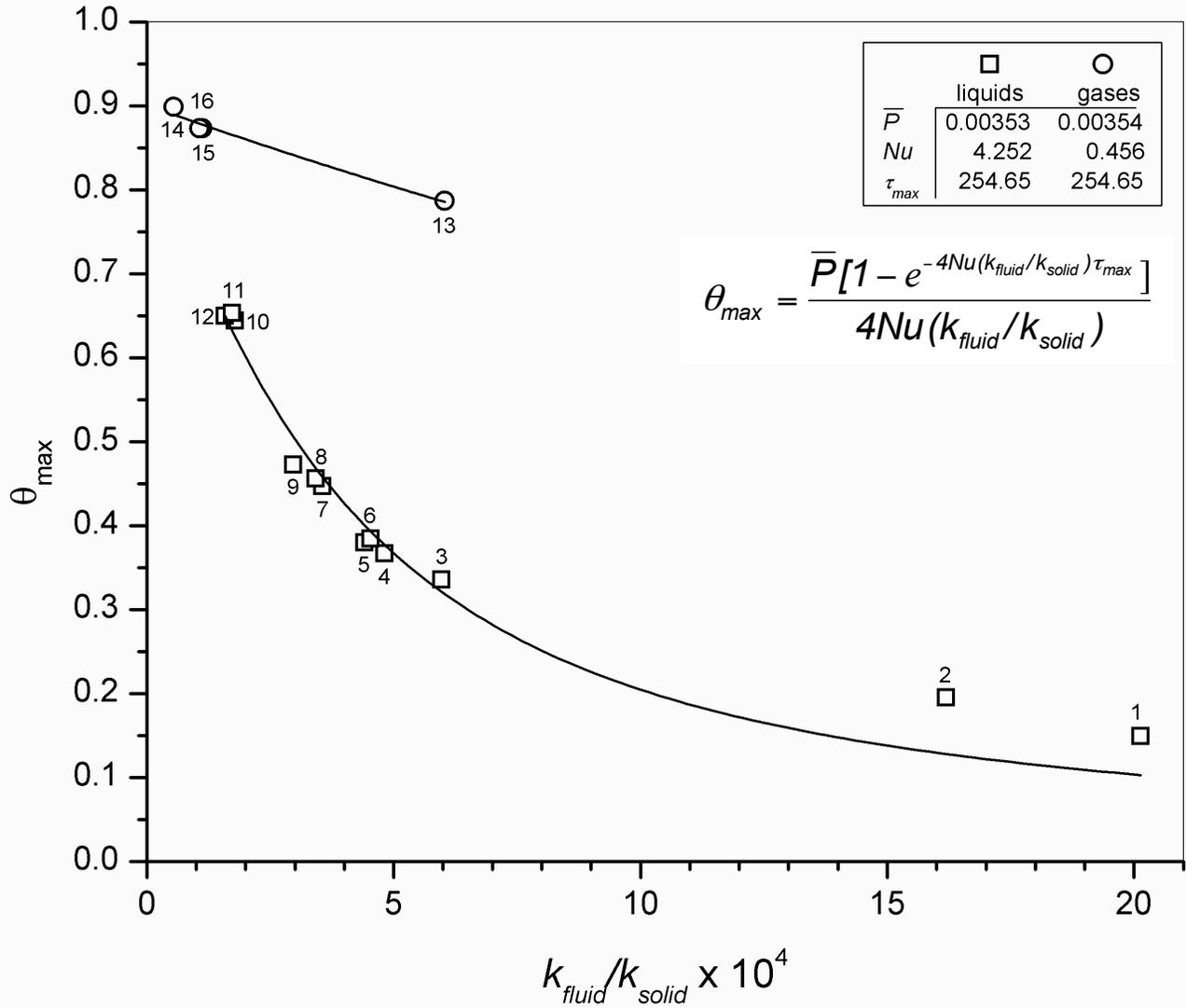


Figure 2: Variation of θ_{max} with ratio of fluid to solid thermal conductivity. Parameters are \bar{p} and Nu . Inset shows regression values that best represent the measurements in Table 1. Numbers correspond to those given for the fluids listed in Table 1.