LABORATORY DEMONSTRATIONS AND BREAKOUT ACTIVITIES

Fire Protection Engineering Design Challenge
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SECTION 1 – DEMONSTRATIONS

1.1 Candle Flame

Required Materials:

- Lighter
- Candle (candles with relatively thin wicks are better than those with thick wicks)
- Glass eyedropper
- Metal grate/mesh
- Loose Index Card

Every demonstration outlined in this document involves modifying one part of the fire triangle/tetrahedron to influence the behavior of fire. It is important to continually remind/question the audience of the importance of the triangle/tetrahedron to further their understanding of fire. Begin this demonstration with questions about the *fire triangle*.

Introductory Discussion:

Questions:

1. What is the fire triangle?
2. What three things are needed to have a fire? (Answer: fuel, oxygen, and heat.)

> Clarify that heat, not necessarily a spark, is the third leg. Heat is required for both ignition and sustaining. Perhaps challenge the group by introducing the fire tetrahedron: fuel, oxygen, heat, and an uninterrupted chemical chain reaction.
> What is a flame?
>
> A flame is an indication that a fast chemical reaction is occurring between a fuel and an oxidizer, it is the point where the 3 elements of the fire triangle combine in the proper proportions. In a chemistry class, this type of reaction would be labelled an oxidation-reduction reaction, or Redox. This reaction results in the release of energy in the form of heat with radiation emitted in a wide range of wavelengths, including those visible to the human eye, hence the visible flame. The location of the flame is an indication of where this reaction is occurring, where the components of the fire triangle (or tetrahedron) are present.

Demonstration Procedure:

Protective eye wear must be worn for this experiment. This experiment should be performed preferably under a hood or at least in a well ventilated room.

Step-by-Step Procedures:

1. Place candle under the hood (turn hood on).
2. Using a long-armed lighter, light candle.

> With the candle lit, ask: "How are the three components of the fire triangle represented by this candle?"

Describing the process of a candle flame, first, the wax in the wick is easily ignited by the external source and initially is the fuel source, however a secondary fuel source is needed to sustain the flame. The flame of the candle is around 1200 to 1500 ℃ (2100 to 2700 ℉). This is the "What is the heat source" part of the triangle. The heat from this flame eventually creates a liquid pool beneath. Through capillary action (how a tree absorbs water through its roots and transports it up the trunk or how a paper towel absorbs water), the liquid wax is absorbed by the wick and transported to the flame, where it is vaporized. Ask them what happens when a liquid is heated. This is the second part of the triangle, "What is the fuel?" Ensure there is understanding that the vaporous wax is what's burning, not the liquid or solid wax.

"Where is the oxygen?" or "What is the third part of the fire triangle, and where is it?" The vaporized wax particles mix with ambient oxygen present in the room to create a combustion process. The combustion process creates energy, we can interpret this energy as light heat, which is released in all directions.

Now discuss the flame shape, and in particular where the combustion reaction is occurring. The first aspect is to discuss where specifically is the reaction occurring, i.e. is it only on the edges or is throughout the entire thickness of the flame? Or, pose the question as to whether the flame is solid or hollow.

Gloves and protective eye wear must be worn for steps 4-8 of this experiment

3. Holding a wire mesh with pliers (or gloves), place the wire mesh at about the mid-height of the flame. Invite audience to look 'inside' flame to see that flame is hollow (NOTE: Do not allow individuals to look in from directly above the flame so their face is in the stream of smoke).

Seeing that the flame is hollow, ask what's in the "clear" space in the middle? By using the glass eyedropper in the next two steps, you can demonstrate that the inner portion of the flame contains fuel vapors.

5. Remove the wire mesh, returning to the original candle flame. Use the glass eyedropper to extract fuel vapors from inside flame by depressing eyedropper bulb while tip is outside of flame, insert tip into center/base of the flame, release bulb to entrain vapors into tube.
6. Reposition tip near top of flame, gently depress dropper blub to release vapors at the top and vapors should ignite.

Why are the vapors on the inside not ignited? Describe the fire triangle once again, the fuel needs to mix with oxygen. Simply put, only fuel is inside of the flame in the "hollow" space. The oxygen is in the ambient air outside of the flame. The oxygen is virtually all consumed on the edge of the flame so that there is not sufficient oxygen to burn the fuel vapors in the middle of the flame.

Next, why does the flame stop at the mesh instead of burning straight through? Again, this can be explored by the fire triangle, in that one of the components must be missing above the wire mesh.

7. Position the wire mesh at the mid-height of the flame again.

    The metal mesh, typically made of steel is colder than the flame. The metal in the wire mesh is also a very good conductor of heat. Because of this, the mesh absorbs the heat from the flame, and conducts it away from the vicinity of the flame to remove heat from the gases moving through the mesh. The process of heat conduction in the mesh is also why anyone conducting this experiment is directed to handle the wire mesh with pliers and not with bare hands as the edge of the mesh gets hot.[1]

    Even though the flame is not present above the wire mesh, a stream of smoke should be present above the wire mesh. This smoke contains unburned wax vapors. The next step will explore that aspect.

8. Demonstrating that smoke contains unburned wax vapors, keep the wire mesh in place at the mid-height of the flame and use the long igniter to ignite the smoke stream (thereby re-introducing the heat component of the fire triangle). You may have to get a volunteer to use the long igniter to re-ignite the smoke stream if you are not confident in your ability to hold the mesh steady and operate the lighter at the same time.

    Why is the stream of smoke apparent in the shortened flame, created when the wire mesh is present and not there when the wire mesh is removed and the flame is elongated? Decreasing the length of the flame, i.e. the length of the combustion zone, the fuel vapors have not had time to be completely consumed. Moving up the flame, the oxygen that was entrained from below the flame and pulled upwards due to buoyancy begins to be depleted. Now there is not enough oxygen to burn cleanly. More products of combustion are being produced. Any darkness in the smoke is due to the presence of soot particles (partially combusted wax vapors).

    Next, let's consider the color of the flame. Ask participants "What color is the candle flame"? A common response will likely be "yellow". However, a careful examination of the flame will result in an observations that the color of the flame change from the base to the tip. The color of the flame is affected by the efficiency of the combustion process at different parts of the flame. At the base of the flame, the ratio between fuel and oxygen is near optimum, meaning near-complete combustion is obtained, with the principal products being CO_2 and H_2O vapor. Higher up the flame, less oxygen is available (as it is displaced by the updraft of combustion products) so more incomplete products of combustion are produced, such as soot. Essentially, soot is unburned carbon. The soot is heated to a temperature at which it begins to glow, radiating light in the yellow wavelength. The yellow wavelength is emitted due to the temperature attained by the soot particles.[2]

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[1] Note: if the demonstration is continued for a long enough time, the portion of the wire mesh over the flame may glow red, which is an indication that sufficient heat is present to allow the flame to propagate above the mesh which should now be visible.

[2] More advanced students can be encouraged to research Planck's Law which dictates this aspect of flames.

Finally, let's explore the aspect of flame shape. Why is the candle flame long and thin, rather than spherical? Answer: gravity. Because of gravity, smoke rises. More specifically, because smoke is hotter than the surrounding air, its density is less than that of air. As such, the smoke is buoyant. While gravity can't be removed in a typical laboratory to allow you to perform a demonstration, a video of an experiment led by Professor Peter Sunderland in the Department of Fire Protection Engineering at the University of Maryland is available where he did conduct experiments in near-zero gravity conditions, referred to as microgravity. He has conducted these experiments both in a tall drop tower and on the International Space Station. In the drop tower, an experiment is dropped from a very tall height to experience "free-fall" conditions for a few seconds. A video of one of Dr. Sunderland's experiments in the drop tower is available at: https://www.youtube.com/watch?v=SZTl7oi05dQ.

1.2 Flame Spread and Heat Transfer

Required Materials:

- Lighter
- 3x5 Index cards (at least 2)
- A ring stand to hold an index card
- Timer

Introductory Discussion:

Questions:

1. Will flame spread more quickly on a material oriented vertically or horizontally?

   Flame spreads across the surface of a material because the unburned fuel in front of the flame is heated up to its ignition temperature by one or more modes of heat transfer (convection, conduction, and/or radiation). The role of the modes of heat transfer can be explored by experiments involving flame spreading across an index card. Differences in the heat transfer mode can be explored by conducting the experiments with the index card oriented at a variety of angles.

2. Start the discussion by considering the index card to be held vertically (don't do the experiment yet). Ask students that if the card is ignited at the bottom (see Figure 1), what modes of heat transfer are going to cause flame to travel vertically along the card?

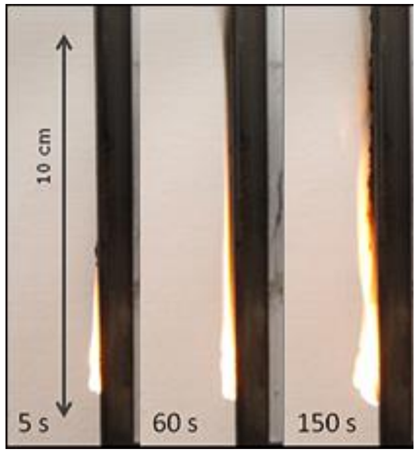


Figure 1. Vertical Sample (Experiment by Leventon, University of Maryland, https://fpe.umd.edu/research/projects/upward-flame)

The flame is adjacent to the vertical sample, but the entire height of the sample next to the flame is not yet burning in any of the time periods shown. In other words, the flame length is taller/longer than the combustion zone. The flame is providing radiative and convective heating to the unburned portion of the sample.

Consider now that the index card is oriented horizontally, such as is depicted in Figure 2. Now, the flame is not adjacent (parallel) to the sample, so the unburned section is only receiving radiant heat as all of the convected heat is rising above (and away) from the sample.

Figure 2. Horizontal Sample

Demonstration Procedure:

Protective eye wear must be worn for this experiment. Gloves should be available to handle the sample. This experiment should be performed under a hood and separated from any combustibles. Have a means available to extinguish the fire once the flame reaches the end of the sample.

1. Place ring stand with clamp to hold card under hood (turn hood on).
2. Attach index card to clamp on ring stand, orienting the card horizontally.
3. Ask someone in the group to be the timer, starting the timer when the card is ignited and stopping when the flame reaches the end.
4. Using the long igniter, ignite the top of the card at the free edge (the one at the end opposite the clamp).

5. Record the total time for the flame to travel the length of the card.
6. Once cool, remove any remnant of the card (caution: the clamp may be hot).
7. Install a new card, but now orient the card vertically.
8. Ask someone in the group to be the timer, starting the timer when the card is ignited and stopping when the flame reaches the end.
9. Using the long igniter, ignite the bottom of the card.
10. Record the total time for the flame to travel the length of the card.
    What was the difference in the times for the flame to transit from one end of the card to the other? The time for the test with the vertical sample should be appreciably less than that for the horizontal sample. This experiment can be repeated with the card oriented at angles in between the vertical and horizontal orientations. A trend should be observed where the closer the sample is to being vertical, the shorter is the time needed to transit the length of the card.

1.3 Suppression

Required Materials:

- Lighter
- Dollar Bill (or index card)
- Beaker of water
- Methanol spray bottle
- 10 ml graduated cylinder

Introductory Discussion:

Questions:

1. Introducing the topic of suppression, ask the audience, “How are fires typically suppressed?” Have the audience brainstorm ideas. How do these suppression systems work? What part of the fire triangle do they eliminate? Discuss fire triangle components again.

    Water is typically used because it is cheap, plentiful and widely available. Water is a great suppression agent because it is excellent at absorbing heat. It has a very high specific heat, high heat capacity, which means that it can absorb an appreciable amount of energy when increasing in temperature and eventually evaporating. This means water can cool fuels by removing energy from the fire.

2. What are the negative side effects of using water to suppress fires? Have the audience brainstorm ideas, which should include destruction to personal property (due to water damage) and the ineffectiveness of water to suppress fires involving some fuels (like oils!).

    This demonstration will highlight the heat absorption capability of water.

Demonstration Procedure:

Protective eye wear must be worn for this experiment. This experiment should be performed under a hood and separated from any combustibles. Have a means available to extinguish the fire in case does not self-extinguish.

1. Completely saturate the dollar bill or index card with water.
2. Place the dollar or card on a metal pan under the hood (turn hood on).

3. Using a 10 ml graduated cylinder measure 0.5 ml of methanol. Pour fuel on top of the saturated dollar bill or card (NOTE: do not use ethanol because it will mix with the water and won't ignite easily).
4. Using a lighter ignite the methanol.
5. Let the flame burn itself out.

Ask the audience why the dollar bill or card didn't burn. Explain how water has a higher temperature of vaporization the methanol, but less than that of the dollar bill or card. Therefore, the dollar bill or card will not burn until all of the water has evaporated. But since the methanol burns faster than the water can be evaporated, the water helps to cool the dollar or card. As a reminder, note that sprinkler systems prevent flame spread by saturating materials with water.

SECTION 2 – BREAK-OUT ACTIVITIES

2.1 Material Flammability

Heat Transfer:

Describe an example for each of the modes of heat transfer: conduction, convection, and radiation.

- Conduction – hand on a coffee cup
- Convection – swimming in a cold pool
- Radiation – sun warming the earth

Ignition of Materials:

Which material would ignite more quickly when exposed to the same magnitude of radiant heat source? Why?

- Enforce the idea of geometry and surface area
- Book will burn slower (thermally thick)
- Paper will burn faster (thermally thin)

Heat of combustion:

Which material has the produce the greater amount of heat if completely consumed, a block of cardboard or a block of wood (same size)?

- Enforce the idea of material property
- They have similar heats of combustion, being somewhat similar chemically, but a volume of wood weighs more than cardboard, being expanded and having air pockets, so per unit of volume the wood will produce more heat.

Bonus question: Which will burn faster, cardboard or wood?

- The cardboard has a greater surface area to mass ratio, so it will burn faster, providing a greater heat release rate.

Heat Generation:

If completely consumed by fire, how many grams of wood will produce the same amount of heat as 2 g of polyethylene?

- The heat of combustion of polyethylene is 43.6 kJ/g. Hence if 2 g of polyethylene is consumed, this will generate 2 x 43.6 = 87.2 kJ of energy.
- Using a heat of combustion of wood of 17 kJ/g, the amount of energy produced by the burning polyethylene (87.2) by the heat of combustion of wood (17 kJ/g) yields a value 5.1 g of wood.

2.2 Suppression

The goal of this activity is for students to design a mini sprinkler system. Tell students they have a shoe box that they need to protect if there was a fire set anywhere inside of it. Have them draw the layout of a sprinkler system, including piping and nozzle location(s). Have students write a brief description about how the system works. The system must be activated in some way by the fire and can only use the materials listed below.

Ask questions such as, “Will the fire get hot enough to actually activate this system?” or “Is every place in the box protected or is there one place that is more protected than another?”

Materials:

- Cup
- Water
- String/ rope
- Straws
- Solder
- Wax
- Plastic containers
- Paper
- Any other very basic material that they want

2.3 Detection

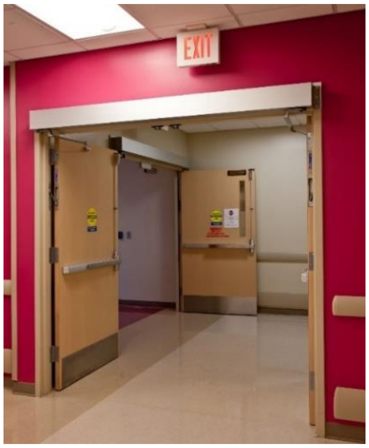
The goal of this activity is for students to design a means of detecting a fire. Tell students they have a shoe box that they need to protect if there was a fire set anywhere inside of it. The fire will consist of burning paper or cardboard. Have them consider what will be produced by such a fire. Then, ask them how such products could be detected by simple items (such as those listed below – feel free to encourage students to think about items beyond those in the list). Have students write a brief description about how their detector would operate. For example, if they indicate that heat would be produced by a fire, how would any of the materials respond to heat (melting, burning, etc.)

Materials:

- String
- Balloon
- Thin plastic film (such as a portion of a plastic bag)
- Popcorn

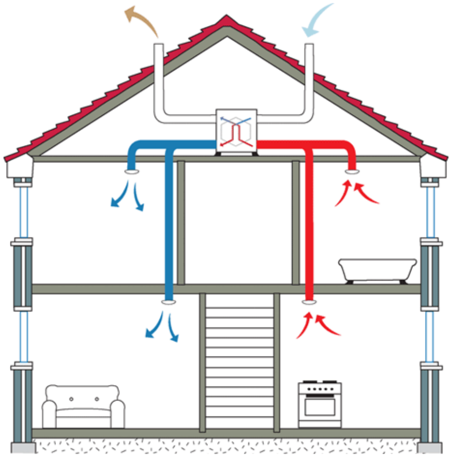
2.4 Compartmentation/Ventilation

1. Fire doors are a key part of a fire protection strategy. If a door needs to be generally open, how can it be closed in the event of a fire?



Responses should include a strategy for detecting a fire and then provide a means to allow a door to swing closed or force it to be closed. An example could include a string that holds up a door that swings down. Upon fire exposure, the string burns through to release the door.

2. Most modern buildings have a ventilation system to move air for heating and cooling as indicated in the figure below. How can a fire protection design use this system to limit the movement of smoke?



Responses should describe how smoke spread travels from a room at a higher pressure to a room or space at a lower pressure. The ventilation system could be arranged by turning off the supply in the fire room (leaving the exhaust on) and turning off the exhaust in adjacent spaces (leaving the supply on). This will create a situation where the adjacent rooms will be at a greater pressure than the fire room. An alternate response, though not necessarily as effective, would be to simply turn off all supply and only exhaust smoke from the fire room (thereby reducing the quantity of smoke that needs to be limited).