Causes and prevention of arcing in 50-ohm pilot scale radio frequency heating system

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Written for presentation at the
CSBE/SCGAB 2018 Annual Conference
University of Guelph, Guelph, ON
22-25 July 2018

ABSTRACT Arcing in the RF applicator causes a very high temperature and can lead to a fire from mild to severe in inside and outside the system. Fire in RF heating system can be avoided and controlled. However, if it is not stopped, directly results in damaging the material being processed, even damaging the processing equipment, and burning the building. This paper discusses the designed applicator for 50-ohm RF heating system which causes the arcing. The 50-ohm RF applicator was designed for disinfection of insect pests in stored grains (batch and inline process). The designed applicator was placed on the wood table and composed of 30 cm diameter tubular channel, 70 cm x 30 cm rectangular electrodes connected to the matching network, and auger which transport and mix the grains while heating. The two electrodes were located at the top (ground) and bottom (hot) of the channel. The first cause of arcing is the material in the designed applicator (grains, wood table, and other arc producing materials) which keeps heated repeatedly and carbonizes. Another cause the arcing in the applicator is the high electric field strength at the edges of the electrodes which are above the air ionization and breakdown threshold. Therefore, this paper gives the solutions to eliminate the arcing problem in the applicator. In addition, suggestions are also given for further prevention of arcing in an RF heating system.
INTRODUCTION Radio frequency (RF) and microwave (MW) heating are a non-chemical method and have been studied as alternatives to chemical use for disinfestation. These methods rely on the interaction of electromagnetic waves and the ions and dipole molecules of the materials (Macana et al., 2018c). A number of review papers (Macana and Baik, 2017; Hou et al., 2016; Marra et al., 2009; Wang and Tang, 2001; Nelson, 1996, 1966; Ark and Parry, 1940) have summarized the study of these methods for disinfestation. The results of their studies showed that RF and MW offer several advantages over other methods: fast, non-contact, and volumetric heating. However, RF heating is preferred over MW heating for disinfestation because of its high penetration depth and selective heating effect (Macana and Baik, 2017; Shrestha et al., 2013; Wang et al., 2011, 2003; Guo et al., 2010; Nelson, 1996). 50-ohm radio frequency is a modern type of RF heating system and it is the first time to be used in disinfestation. This heating system offers many advantages compared to the conventional type. Nevertheless, there is always a problem which is common to MW and RF, especially when the heating system is not properly designed and the workers have no knowledge about this problem (arching). The arcing in RF and MW heating system is one source of a fire. It can damage the product and the processing equipment. In RF and MW for batch and continuous process, common sources of arcs are super dried product which leads to charring and carbonization. For example, product caught in the conveyor belt in RF and MW continuous process or a piece of meat and bacon in a batch process which keeps repeatedly heated carbonizes and causes arcing (Shiffmann, 2001). Another source of arcing is contamination of any arc producing materials such as metal in the RF or MW heating system (Sun et al., 2016; Moonngilan, 2009). Lastly, the high electric field strength which is above the air ionization and breakdown threshold causes the arcing (Sun et al., 2016; Moonngilan, 2009).

Therefore, this paper deals with the understanding and causes of arcing and fire on the designed applicator for a 50-ohm pilot scale RF heating system. In addition, suggestions are given for prevention of arcing.

THE DESIGNED APPLICATOR FOR 50-OHM RF HEATING SYSTEM Figure 1 shows the design of applicator for 50-ohm RF heating system placed on a wood table for elevation. The applicator has two aluminum electrodes (parallel plates), the grey at the top (ground) and red at the bottom one (hot). The dimensions of both electrodes are 70 cm in length and 30 cm in width. In addition, in between the two electrodes, the 30 cm tubular channel (made of polypropylene) is placed. The applicator was designed to kill the insect pests in stored agricultural materials with the 50-ohm technology based RF heating system. The materials (mixture grains and insect pests) are treated in the channel and act as dielectric materials during the RF heating.

The designed applicator is connected to the other parts of the 50-ohm RF heating system: RF generator (0-15 kW, 27.12 MHz), 50-ohm coaxial cable, and automatic matching network (Figure 2). The RF generator is the source of electromagnetic waves (signal) and connected to the matching network by a 50-ohm coaxial cable. The matching network receives the signal from the generator and gives the signal to the designed applicator. The matching network makes sure that
the applicator receives the maximum signal. The matching network is one of the advantages of this system which balances the impedance of the system to have maximum power transfer to the load.

Figure 1: Designed applicator with the auger system: (a) Left view (b) Right view (c) Front view (d) Top view (Macana et al., 2018a)

Figure 2: Parts of 50-ohm RF heating system: (a) 50-ohm cable (b) RF generator (c) Automatic matching network (Macana et al., 2018b)
HOW DOES FIRE START IN RF AND MICROWAVE HEATING SYSTEM? The fire in RF and MW heating system is common and can be avoided with proper knowledge about this problem. However, the physics and chemistry of fire are very complex. Therefore, this paper made it simpler to understand the basics of fire. There are three components to make fire happens: fuel, heat, and oxygen. These components are commonly called “The fire triangle” (Figure 3). A triangle has three sides. The first side of the triangle is fuel and its sources can be solid, liquid, and gas. For example, in solid forms (wood, plastic, agricultural materials, leaves); in liquid forms (gasoline, alcohol); and in gas forms (carbon monoxide, natural gas, propane). The second side is heat and its sources are sparks, sun, and friction. The last but not the least side is oxygen. Oxygen is present everywhere. A triangle can exist if all sides are present. Similarly, the fire can start if all the three components are present. Removing one of them can stop the fire. For example, covering the fire with fire blanket distinguish the fire because the oxygen was removed. In the same way with the fire distinguishers, it was designed to remove one or more of the components in the fire triangle to stop the fire. Some are designed to remove the fuel and oxygen. This is dependent on the type of extinguisher.

Figure 3: The fire triangle (UPFS, 2016)

ARCING One of the sources of heat is arcing. This is the common initiator of fire in RF and MW heating system. Arcing is also known as an electrical discharge or spark. It happens when the molecules or atoms of the surrounding air between the two electrodes (hot and ground) got ionized and become conductive (Moonngilan, 2009). The current from the electrode can pass through the air going to the opposite electrode (back and forth). When this happens, arcing discharge (plasma discharge) starts and the resulting temperature can reach from 3000°C to 10,000 °C (Hines, 2018). This very high temperature can damage the materials of the RF applicator and it can create ignition easily to the materials. Other sources of arcing are coming from the materials being heated in the RF applicator. For examples reported from Shiffmann (2001), materials which undergone charring and carbonization because excessive dehydration leads to arcing. Another example that is common to microwave and RF heating system is contamination of metal and arc giving materials (carbon soot). Therefore, arcing in a 50-ohm RF heating applicator can start a fire which can damage the processed materials, RF applicator heating system, and if it is not suppressed, it might burn the whole building.

HOW DOES ARCING AND FIRE HAPPEN IN THE DESIGNED APPLICATOR FOR 50-OHM RF HEATING SYSTEM? As discussed earlier, the fire can start if all elements (fuel, heat, and oxygen) are present. In RF and MW heating system, arcing is the source of heat and it is
common problem for both batch and continuous processing. Therefore, this section explains why arcing happened in the designed applicator. Figure 4 shows the photographs of applicator after the arcing and fire happened. At that time, the system was run to high power (11 kW out of 15 kW) and noticed arcing and fire in the tubular channel (polypropylene) and the table (wood), which are close to the hot electrode at the bottom. In the photograph, at the corner of the hot electrode shows marks of burning and arcing (Figure 5). This shows that there are high electric fields at the corner of the electrodes which might cause the arcing and leads to a fire. This happens because of the edge heating effects of the electrodes (Shiffmann, 2001). However, the assumption was not sure because there are other sources of arcing as discussed earlier. To confirm the assumption, several improvements of the applicator were done. The edge and corners of the electrodes were rounded especially at the high electric fields. Since the hot electrode was laid over the wood table, the high electric field might cause the burning of the table. Thus, lifts were put between the tubular channel and wood table to minimize the electric field effect on the table. An air gap is the most effective barrier to electric field strength.

After for all the changes in the applicator, the system was partially cleaned and ran starting at low power. However, upon adjusting the power level reaching to just 2 kW, arcing happened and suddenly smoke came out as a sign of fire in the applicator. The photograph of the applicator after the second arcing and fire happened is shown in Figure 6. This confirms that the high electric field at the corners and edges of the electrodes is not the only contributor to arcing. The other source of arcing in the designed applicator is any arc producing materials. For example, the carbon soot after the burning of the wood table and the polypropylene channel can cause the arcing.

Figure 4: Photographs of the applicator after arcing and fire happened at 11 kW and 27.12 MHz
Figure 5: Marks of burning and arcing at 11 kW and 27.12 MHz

Figure 6: Photograph of the designed applicator after the second arcing and fire happened at 2 kW and 27.12 MHz
After finding out the other sources of arcing, the designed applicator was modified again for the better. The carbon soot in the table, channel, electrodes, and other parts of the applicator was removed. The removal of carbon soot was really difficult, especially for the polypropylene tubular channel. After the arcing and fire incident happened, it is really significant to clean up thoroughly the burnt marks. Once it happened, it is likely to happen again. Hence, skimming off some of the damaged surfaces of the applicator to remove the carbon soot is important. Using abrasives to clean is a good idea but is difficult to the channel where marks of arcing are very thick. So, some part of the channel was totally removed and replaced by Teflon, which is better than the polypropylene but it is more expensive. Another thing done was cleaning the spill grains under the hot electrode. Once grains are overheated and dehydrated can also trigger the arcing.

**PREVENTION OF ARCING AND FIRE IN 50-OHM RF HEATING SYSTEM** 50-ohm RF is a modern type of RF heating system. The principle is similar with the conventional type RF and microwave heating system. RF and MW, which are electromagnetic based, are part of the electromagnetic spectrum. This means that the heating mechanism of RF and MW rely on the interaction of the materials and electromagnetic energy. Therefore, in preventing arcing and fire in 50-ohm RF heating system, a similar approach is applied to conventional RF and MW.

*Prevention of arcing and fire* The following are the suggestions to be done in preventing arcing and fire.

- **Applicator.** In dielectric heating using RF and MW energy, the applicator is where the materials being heated. This is where arcing and fire commonly happened. Most of the cases, the effect is mild because arcing and fire are confined in the applicator. However, the severity of fire is really dependent on the situation. Therefore, prevention of arcing and fire in the applicator is important before it becomes worst. To avoid arcing in the applicator, regular checking and maintenance of all the parts of the applicator (electrodes, tubular channel, auger, conveyor, cavity, metal shell, etc.) should be done before starting the process. Make sure all the parts are clean with no carbon soot, and other arc producing materials. Make sure also that there are no combustibles (wood, waste grains, food, etc.) near the hot electrode. When these materials get overheated create fire and start the arcing or create the arcing and start the fire.

- **Materials to be heated.** The materials to be heated depend on the type of application of RF and MW energy. For MW for example, most of the houses in Canada have a microwave as part of the basic appliances in selling and buying the house. This household microwave oven has been used in heating food. Similarly, with the RF heating system, the design is based on the type of application. For this study, the RF energy was applied for disinfestation of insect pests in stored agricultural materials. Hence, the materials to be heated are the mixtures of insect pests and grains. Just like the microwave, there are things to consider in avoiding arcing and fire in the system. First, the materials to be heated should be free of contamination of arc producing materials such as pointy metals. When metals are heated by RF and MW energy, the charges on the metal move back and forth depending on the skin depth (penetration depth) of the metal. Thus, if the metal has sharp edges, it has high electric field intensity at the edge. The charges at the edge jump because of its enough kinetic energy resulting in the ionization of air (Sun et al., 2016). Any metal mixed in the materials should be avoided. To do this, a metal detector should be installed in the entrance of the applicator. Second, the materials should not be over dehydrated which carbonized and results to arcing. This is very common in MW and RF processing where some materials to be heated are stacked in the conveyor and repeatedly heated. Therefore, regular checking of the applicator is needed before the process.
• **Atmosphere.** The arcing and fire is dependent also on the atmosphere on the applicator. A flammable atmosphere of the applicator should be avoided such as aerosols of oily vapors from high-fat materials. This results in condensation on the side of the applicator and become highly flammable (Shiffmann, 2001).

• **RF generator.** The RF generator is the source of the electromagnetic energy supplied to the load. There are few suggestions to do in the RF generator in preventing arcing and controlling fire. The empty applicator should be avoided in running the RF generator. This results in arcing causing ignition of applicator components (Shiffmann, 2001). The components of the applicator might melt because of overheating. Another important thing to note is that RF generator continues to run even arcing and fire exist. This leads to a more severe arcing and fire if RF generator is not shut down. In running again the generator after the arcing and fire happened, avoid the sudden increase of power in the RF generator. The abrupt changes of power can create arcing in the applicator even a small arc producing material exists.

**CONCLUSION** Arcing and fire are common phenomenon in radio frequency and microwave heating system. Arcing in RF and MW heating system is a source of extreme heat and can cause a fire from mild to severe in the system. Therefore, this paper discussed the basics about arcing and fire and their cause to the designed applicator for 50-ohm RF heating system and suggestions were provided for prevention of arcing and fire. This paper found that the cause of arcing and fire in the applicator are the arc producing materials (over dehydrated wood and grains in the hot electrode, carbon soot present in the applicator and the high electric field strength at the edges and corner of the electrodes. Thus, solutions were provided accordingly. The first solution was complete removal of arc producing materials such as spill grains under the hot electrodes and carbon soot in the applicator after the incident happened. The second solution was rounding off the corner edge of the electrodes to reduce the electric field intensity at that point. Lastly, an air gap is provided between the polypropylene tubular channel and the wood table to avoid overheating the table.

**Acknowledgments.** The authors are grateful for the financial support of the Saskatchewan Ministry of Agriculture and the Western Grains Research Foundation, Saskatchewan, Canada through the Agriculture Development Fund program (ADF #20130219) for this study. The authors gratefully acknowledge also the contributions of the following persons: Rlee Prokopishyn, the technician of University of Saskatchewan Chemical and Biological Engineering Department for helping us during the design and installations; Blair Cole and Daniel Vessey from University of Saskatchewan Engineering Shops for helping us with the fabrication; Ian Armer and Mike O’Brien from Viterra Inc. for providing us grains; and Oliver Broad from Coaxial Power Company Limited for providing as technical assistance.

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