Researching the Ultimate Fireless Steam Locomotive - Part III

Contributed by Harry Valentine, Transportation Researcher

Despite its short operating range and low power, the fireless steam locomotive incurred extremely low maintenance and operating costs. The thermal storage material (saturated water) was easy to replace and typically cost little. Driving staff was easily trained and fireless locomotives typically offered long service lives. During the era of fireless steam railway operation, numerous efforts were made to improve efficiency, raise power output and extend the operating range of these locomotives.

In the modern era, fireless steam locomotives can be recharged from concentrated solar thermal energy (using heliostats or solar collectors), from heat-pumped geothermal energy as well as from a variety of stationary combustion systems. In terms of overall energy efficiency from energy source to drawbar, fireless steam locomotives can still offer competitive efficiencies against other more modern technologies. Despite the demise of steam locomotives from mainline railway operation, research and development in related fields of thermodynamics and thermochemistry continually produce new ideas and concepts that can actually improve the performance of steam locomotives.

Compound Accumulators:

Ongoing research and into metal alloys and insulation technology has resulted in the development of spherical accumulators that can hold steam in the ultra-supercritical superheated region. Such a device can be installed on to a locomotive chassis, along with a more traditional high-pressure accumulator. In operation, superheated steam from the ultra-critical accumulator can be fed into the lower pressure accumulator with the result that locomotive power output and operating range can be extended. The spherical accumulator would be recharged by flowing superheated steam through a coiled pipe containing a series of choke valves and located below water level inside the accumulator. A spherical container of heat of fusion material inside the spherical accumulator would assist in maintaining the steam in it in the ultra-critical temperature and pressure range.

The lower pressure accumulator would be recharge by injecting superheated steam through a pipe system located below water level near the bottom of the accumulator. As the pipe enters the accumulator, its diameter would increase along its length (a diffuser) before splitting into 4-pipes that would each contain a choke valve as the pipes recombined into a perforated section. Saturated steam would be injected into the water inside the accumulator through holes in the perforated pipe. As the steam passes through the pipe system, its temperature and pressure would initially drop from 1,000-psia @ 700-deg F to 540-psia @ 550-deg F to 310-psia @ 422-deg F. The pressure in the accumulator would eventually rise to 1,000-psia and its temperature to 545-deg F.

Metal Heat Storage:

During the first half of the 20th century, molten sodium hydroxide (NaOH or caustic soda) was used to store thermal energy in fireless steam locomotives in Denmark as well as in the UK. The performance results were less than spectacular and the heat of fusion locomotives were soon withdrawn from service. NaOH has a density of 1.72 and melts at 320-degrees C (608-degrees F) with a latent heat of fusion of 77.4-BTU/lb. It is corrosive and its thermal conductivity decreases as temperature increases. However, the early experiments involving this heat of fusion technology provided a foundation upon which further research into the use of stored thermal energy may be undertaken.

Recent advances in thermal energy storage technology have involved combining similar metallic oxide compounds so as to lower the overall melting temperature while raising the latent heat of fusion. These advances come at a time when new corrosion-resistant, high thermal-conductivity ceramic material such as silicon-carbide and silicon-nitride are becoming commercially available. Materials now available from the aluminium industry offer the potential to develop materials with high latent heats of fusion and high thermal conductivity and that melt at temperatures that can generate steam.

Aluminium Compounds:

The aluminium industry is offering several types of naturally-occurring bauxite ore that can be used as low-cost thermal energy storage material. Two of the ores have the chemical formula and are named BÃ¶hmite which melts at 350-degrees C (662-degrees F) and Diaspore which melts at 450-degrees C (842-degrees F). Both have a density of 3.4 and the different melting temperatures are caused by a difference in how one oxygen atom is double-bonded to the tri-valent aluminium atom.

At 300-degrees C (572-degrees F), aluminium has over 5-times the thermal conductivity of sodium. While it is possible to use BÃ¶hmite directly as a thermal storage material, mixtures of various aluminium oxides offer potentially higher latent heats of fusion. Alumina (Al2O3) has a density of 3.8, melts at 2045-degrees C with a latent heat of fusion of 460-BTU/lb. When mixed with Diaspore (AlO(OH)), the melting temperature of the compound would drop to under 400-degrees C while its latent heat of fusion would exceed 500-BTU/lb. Beryllium aluminate (BeAl2O4) melts at 1870-degrees C with a latent heat of fusion of 580-BTU/lb. When mixed with Diaspore, the melting temperature of the compound could also drop to under 400-degrees C (752-degrees F) while its latent heat of fusion would exceed 600-BTU/lb.

While the latent heat of fusion of eutectic aluminium compounds could exceed 1,000-BTU/lb, there is the danger of their melting temperatures dropping to below 300-degrees C. This would reducing their potential for use as thermal storage material in fireless steam locomotives. As an alternative mixture, aluminium sulphate (Al2(SO4)3) that melts at 770-degrees C can be mixed with either alumina (Al2O3) or beryllium aluminate (BeAl2O4) to yield a more useful temperature range. Alumina mixed with hydrated silicone dioxide forms a clay

($Al_2O_3.2SiO_2.2H_2O$) that melts at 425-degrees C (797-degrees F) and which can also be used as thermal storage material.

Aluminium occurs in abundance in nature. It is competitively priced and when its oxides are used as thermal energy storage material, can offer many times the usable life expectancy of chemical-electrical battery technologies. Eutectic aluminium phase change materials would be able to offer energy storage densities and operating efficiencies that would be competitive with other modern renewable/rechargeable technologies. At the present time, several aluminium companies have begun research aimed at developing aluminium polymers (giant molecules). This research could lead to the development of compounds that have extremely high latent heats of fusion at desirable temperatures.

PCM Storage and Operation:

The eutectic phase-change-material (PCM) would be carried in torpedo-shaped containers either made from or lined with silicon-carbide or silicon-nitride, both of which are corrosion resistant and the former having extremely high thermal conductivity. Heat would be transferred from the PCM to the steam via conduction, that is, extra material on the steam pipes would be in direct physical contact with the outer surfaces of the PCM containers. The steam pipes, the reheat pipes and the PCM containers would be insulated as a complete system. Alternatively, high-pressure steam from the accumulator could come into direct contact with the torpedo-shaped PCM containers, to maximize the contact area from which the steam may receive heat.

The PCM reheat pipes could recirculate superheated steam supplied and reheated by an external source. The pipes in this case would contain multiple choke valves to force the superheated steam to transfer large quantities of heat into the PCM containers, remelting the PCM for re-use during thermal recharge operations. Such a heat transfer system would be used for PCM's that melt above 700-degrees F (370-deg F). For
PCMs that melt below this temperature, a heat pump system filled with saturated water at pressures up to 3100-psia would be used. Saturated steam could transfer large quantities of heat into the PCM system after passing through a single choke valve.

For systems using high melting temperature PCMs, heat could be transferred into the PCM storage system by using a series of heat pipes. This system would be connected to the locomotive accumulator via a multipass steam pipe. Another high-temperature system would use a sodium-potassium mixture flowing inside a network of stainless steel tubes. A small tank of high-temperature
PCMs may best be used to superheat steam to a higher temperature prior to its expansion in an engine.

PCM/Accumulator Operation:

A fireless steam locomotive could operate with both an accumulator containing saturated water under high pressure as well as a PCM container system. Both systems may be mounted on to the same extended locomotive frame, or the two systems may be mounted in a Garratt layout. A steam line from the accumulators steam dome would first pass through the PCM container system where it would be superheated, before returning to the accumulator inside the steam line.

Once inside the accumulator, the diameter of the steam line would increase (a diffuser) and divide into a series of parallel pipes that would make several loops in a layout similar to that of a water-tube boiler. Heat from the winding steam line would heat the saturated liquid in the accumulator, partially replacing heat that was used to vapourise the liquid that originally entered the steam line. This high-pressure steam would hold over 1600-times the density, 4-times the heat capacity and 8.4-times the heat conductivity of combustion air flowing in locomotive boiler fire tubes. To regulate the temperature of the superheated steam re-entering the accumulator, a bypass line with a flow rate control valve would connect between the line sections leaving and re-entering the accumulator.

Before the steam line leaves the accumulator for the second time, the steam lines would recombine into 4-lines that will have a 1:2:4:8 mass flowrate ratio. Each line would have a choke valve would be located near the accumulator exit point. The choke valves may either be open or some closed during operation, thereby providing 15-equally spaced mass flowrates of steam. As the cooled superheated steam passes through the choke valve(s) at sonic speed, pressure and temperature would be reduced. This heat would replace the heat originally taken from the saturated liquid to flash into the steam entering the steam line as well as the small amount of heat lost through the accumulator insulation.

After its second departure from the accumulator, the steam line would hold lower pressure steam that would be reheated and superheated in the PCM system, before being expanded in an engine to produce traction. Its maximum pressure would be 54% to 58% that of the accumulator pressure. If the steam in the accumulator was 1000-psia @ 544-deg F, the choked steam would leave at a maximum pressure between 540-psia to 580-psia and with a temperature of 475-deg F to 482-deg F.

If the steam expander operates at lower pressure (250-psia to 400-psia), the steam pressure downstream of the accumulator could drop to that pressure level. A PCM that melts at 350-degrees C or 662-degrees F could raise temperature in the steam line to over 600-degrees F, assuming a heat transfer effectiveness of 70%. Steam at pressures under 580-psia and @ 600-deg F would be superheated steam. This steam may be further superheated (to 830-degrees F) by heat from a small onboard container of high-temperature (500-degree C or 932-deg F) PCM.

Condenser Operation:

In order for exhaust steam to be condensed for re-use, the steam would need to be expanded in an oil-free engine. One oil-free option would be to use a water-based graphite lubrication for sliding surfaces of a positive-displacement steam engine. Engine lubricating oil has been known to foul condensing equipment. The concept fireless steam locomotive would use a well-counterbalanced expander that could operate at extremely short inlet valve cut-off ratios, perhaps even under 5% to enhance efficiency. Electrical transmission or modern direct-drive technology may be used.

Exhaust steam from the expander would flow into an expansion chamber (a diffuser section where diameter increases along its length). Steam velocity would decrease in the diffuser as its pressure is marginally increased. The diffuser would connect into several parallel pipes that recombine into an adjustable water-cooled choke valve, the settings of which would be determined by the upstream steam line choke valve settings and the engine inlet valve setting. The water pipes and choke valve(s) would be submerged in high-pressure feedwater.

A vacuum fan operating downstream of the water-cooled valve would increase the pressure difference across the valve. The increased pressure differential would allow more heat to be removed from the cooled exhaust steam passing through the valve at sonic speed. A higher proportion of the steam would be changed into high-temperature liquid water that would be further cooled in the parallel-flow/counter-flow radiators.

Feedwater Heater:

The diffuser, parallel pipes and choke valve all would be housed inside the feedwater heater and submerged in feed water. A large proportion of the latent heat of vapourization of the low-pressure exhaust steam could be transferred into the high-pressure feedwater coming from the locomotive radiator, in which hot water (exhaust would be cooled). Exhaust steam at 60-psia @ 293-deg F could transfer some 900-BTU/lb to the cooler (150-degrees F), high pressure feedwater. The multiple radiators would be able to transfer over 263-BTU/lb of exhaust heat to the atmosphere, on a locomotive that could develop up to 2,000-Hp.

A heat pump may be used to assist in transferring heat from the expander exhaust into the feedwater. Water at 1,000-psia @ 150-deg F would be able to absorb a high proportion of the reject engine heat. The heated feedwater would be heated by energy from the PCM system prior to it being added to the accumulator, which would provide the locomotive with the reserve capacity needed to perform arduous tasks. A condenser and feedwater heater installed in a PCM fireless steam locomotive could extend its operating range depending on the amount of energy contained in the PCM storage system.

Locomotive Performance:

A locomotive carrying 150,000-lbs of PCM with a heat of fusion of over 1,000-BTU/lb would have over 58,000-Hp-hr of available energy. If 18% of this was converted into traction (10,000-Hp hr), a locomotive could operate for up to 6-hours at 1,500-Hp or up to 9-hours at 1,000-Hp (40-mi/hr in excursion service). Higher engine efficiencies that increase power output and extend the operating range could be possible if superheating were done chemically. This approach would involve chemically reacting a metallic-oxide with a small amount of steam to form a metallic hydroxide, at high temperature.

In layout, a PCM fireless locomotive could resemble a Garratt in that the PCM would be carried in the forward and rear sections, while the centre section carries the accumulator. Parallel-flow/counter-flow radiators would be mounted on each side of the forward and trailing sections, for a total of 4-such units. The locomotive could carry over 400,000-lbs of PCM (200,000-lbs in each section) and be capable of operating for up to 10-hours at over 2,500-Hp at the drawbar, perhaps covering distances of up to 500-miles in a day prior to needing a thermal recharge.

For short-distance intercity operation (branch lines, short lines, excursion lines), a non-condensing version of a PCM fireless steam locomotive may be desirable. Such a unit may use more than one high-pressure accumulator that would receive thermal energy from the onboard PCM storage system. Operating distances of up to 200-miles at speeds of 40 mph may require up to 1,000-Hp, after which the PCM storage system and useable capacity of the accumulator would both be exhausted.

Conclusions:

Advances in high-pressure accumulator technology, advances in the research of eutectic phase change metallic oxides, the development of corrosion resistant materials such as silicon-carbide and silicon-nitride, combined with numerous advances in the field of thermodynamics can all contribute to the development of a new-generation fireless steam locomotive. The useable life expectancy and capacity of emerging thermal energy storage material makes it competitive with such rechargeable energy storage technologies as electric batteries (limited life under repeated deep-cycle operation, disposal problems), flywheels (potential to shatter), cooled compressed gas (low energy efficiency), hydrogen technology (low efficiency when recharged from thermo-electric sources).

Despite the demise of steam locomotives from railway service, modern scientific discoveries and modern technological advances offer renewed hope to make modern fireless steam locomotives feasible and competitive. They can be recharged from concentrated solar energy, geothermal energy, or heat generated at stationary plants that process fuels that would be regards as quite unsuitable as a transportation fuel. From the primary energy source to the locomotive drawbar, the theoretical modern PCM fireless steam locomotive would compete against other contemporary technologies. Research into thermal energy storage technology could lead to the development of eutectic and chemical compounds that could offer storage densities that approach 1-Hp-hr/lb.

Published at International Steam website September 5, 2005.