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DIRECT POWER EXTRACTION WITH OXY-COMBUSTION: AN OVERVIEW OF MAGNETOHYDRODYNAMIC RESEARCH ACTIVITIES AT THE NETL-REGIONAL UNIVERSITY ALLIANCE (RUA)

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Abstract:

In conventional oxy-fuel power generation scenarios, oxy-fuel combustion provides no significant advantage other than to simplify CO_2 capture. So in terms of power production and efficiency, the energy and costs required to produce that oxygen are a burden. However, the high temperatures possible with oxy-fuel combustion can enable direct electric power extraction from high-temperature electrically-conductive gases using magnetohydrodynamic (MHD) principles, which would then be followed by a steam cycle also producing electricity. The combined system would produce a high CO_2 exhaust stream - yet with efficiency that may exceed today's best coal power systems. The concept of adding an MHD topping unit to a coal fired power plant in order to directly extract electrical power is not new, and significant effort was made in this direction from about 1973 to 1993. During this time period, it was shown the MHD concept worked in the sense that power was generated, but ultimately development was discontinued due to the high cost of designing, constructing, and operating a complete MHD-steam plant. Additionally, there were a number of technical challenges associated with the technology. Some specific issues cited for coal MHD were slag removal problems, MHD channel operation problems, and cost effectiveness of seed utilization. In this paper, we revisit the use of MHD technology in the context of using it with oxy-combustion to enable cost effective carbon capture. Ongoing research activities within the National Energy Technology Laboratory – Regional University Alliance (NETL-RUA) to address legacy MHD power challenges, and apply new computational tools to MHD power systems are presented. Much has changed since earlier MHD studies: oxygen supplies have become less expensive (because of interest in oxy-fuel for CO_2 control). Superconducting magnets have improved substantially. Perhaps the most dramatic technological improvement since previous MHD efforts is in the area of computational modeling. Today, we have three dimensional multi-physics models that could be utilized to design a more effective system (combustor and generator). To begin addressing the combustion issue, current work applies transported probability density function methods to solve the high-temperature combustion problem. An MHD generator model, which considers fluid dynamics and heat transfer, as well as relevant MHD equations involved in the process, is presented. The modeling efforts also address issues in using wall functions to bridge the laminar sublayer to the fully turbulent boundary layer when Lorentz force is dominant or equally important as compared to other forces.

1. Introduction

One of the more widely investigated approaches for reducing carbon emissions from existing or new coal power plants is in the adoption of oxy-combustion technology. A number of large scale oxy-coal power demonstrations are underway or being built around the world including the planned Future Gen 2.0 installation in the United States. The most prevalent approach for oxy-fuel is to mimic air firing heat transfer characteristics by diluting the oxidant with a significant amount of recycled flue gases so that existing equipment and system knowledge can be utilized [1]. The largest energy penalty associated with conventional coal oxy-combustion is from the power needed to run the air separation unit (ASU) plant to produce oxygen, followed by the power needed for the carbon dioxide compression unit (CPU) , followed by the power needed to run flue gas recycle (FGR) fans to dilute the oxidant and reduce flame temperature; for example these penalties have been found to consume 15.8%, 9.5% , and 4.6% of the oxy-fuel plant's gross electrical power respectively [2]; Huang et al. estimated this leads to a coal plant (using a supercritical Rankine cycle) having only a 30.2% HHV thermal efficiency [2]. Additionally, there is significant capital investment needed to deploy oxy-fuel. NETL's Office of Planning and Analysis has estimated deployment of state of the art oxy-fuel would result in a 54.6% increase in the cost of electricity as compared to deploying a baseline supercritical coal plant [3]. The ASU contributes 65.3% of the increased cost [3]. Because of these costs, oxy-combustion is likely to be used for power generation only if regulations require carbon dioxide emissions control.

While the current approach to oxy-combustion is challenged by the extra cost and energy associated with producing oxygen, researchers in the NETL-RUA have recognized there is a potential game changing aspect inherent to oxy-combustion – which could result in less CO_2 produced per megawatt as well as readily capturable flue-gas. The key is to convert that oxygen potential to work, rather than simply burning the coal (or any fuel) with flue gas diluted oxygen to create heat for a steam boiler. Instead, the high temperatures possible with pure oxygen combustion can enable direct electric power extraction from high-temperature electrically-conductive gases using magnetohydrodynamic principles. Heat remaining after this extraction may then be used in a steam cycle also producing electricity. The combined system would produce a near pure CO_2 exhaust stream - yet with efficiency that may exceed today's best coal power systems. This approach would make oxy-combustion an efficiency advantage, and yet would be ready to provide CO_2 for use or storage.

The concept of adding an MHD topping unit to a coal fired power plant in order to directly extract electrical power out of coal combustion-products is not new. In fact, the United States Department of Energy spent over a billion dollars (in 2012 dollars) to develop MHD power based technology from 1978 through the end of 1993 [4]. The culmination of this program resulted in a demonstration of the MHD topping cycle at the component development and integration facility (CDIF) in Montana. The technology worked in the sense that power was generated, but ultimately the program was discontinued due to the high cost of designing, constructing, and operating a complete MHD-steam plant [5].

In this paper, we revisit the use of MHD technology in the context of using oxy-combustion for cost effective carbon capture. To provide some background on the subject, the history of MHD power is briefly discussed and some basic aspects of MHD power generation are covered. Next, ongoing research activities within the National Energy Technology Laboratory – Regional University Alliance (NETL-RUA) to assess previously identified issues with MHD power and to apply new computational tools to MHD power systems are presented.

1.1 MHD Power Generation History

The founding principles for MHD power were largely discovered in the 1800s. The first significant event may be Faraday's discovery of the law of induction in 1831, and in 1832 Faraday attempted to measure the voltage induced by the flowing Thames river and earth's magnetic field [6]. Also of note was the formulation of Maxwell's Equations in the 1850s and 1860s. In 1879, the discovery of the Hall Effect was made by Edwin Hall. Finally, more than 40 years later, in 1920, Saha formulated his theory on thermal ionization, finalizing the foundational theories behind MHD power generation [7].

In 1938 a Hungarian named Bela Karlovitz undertook the first modern MHD experiments and in 1940 he filed for an MHD generator patent called "Process for the Conversion of Energy" [8]. Incidentally, this system utilized an electron gun in an attempt to enhance gas conductivity - an approach later realized not to be practical when using combustion products as the working fluid [7]. From 1954 to 1960 Richard Rosa experimented with adding potassium carbonate seed to a 10 kW_e MHD generator, thus marking the first approach which was similar to later MHD Power approaches [7]. By 1973, due to the energy crisis, interest in MHD power generation accelerated in the United States and the Energy Conversion Alternatives Study (ECAS) was commissioned to examine conceptual designs of coal-based power systems. Phase 2 of the ECAS was completed in 1976, and the open-cycle MHD system with a steam bottoming cycle was found to have the highest overall efficiency of the 11 systems examined [9]. MHD power development was also well underway in the Soviet Union with the U-25 natural gas powered MHD pilot plant being commissioned in 1975, and in 1976 it achieved the rated power output of 10-12 MW_e [10].

Many of the concepts as well as facilities completed or started during the 1970s were reincorporated into MHD research when the DOE's MHD Proof of Concept (POC) program was established in 1984, a program established as a result of a consensus between government and industry representatives [11]. In 1985, the Component Development and Integration Facility (CDIF) undertook its first coal-fired experiments and coal-fired MHD power was supplied to the power grid [8]. By 1994, 1,300 hours of MHD electrical generator tests had been completed, and the POC channel had successfully been tested at the CDIF for over 500 hours [11]. After this point, MHD power development largely took a back seat to other initiatives and U.S. efforts largely came to a halt. After 1994, much of the experimental work reported came from a Japanese research group at the Tokyo Institute of Technology who were focused on a closed cycle MHD approach with the disc geometry. By 1999, the Japanese "FUJI-1" facility had achieved a peak enthalpy extraction ratio of 18.9%, a record for the facility [12]. Outside of this work, most of the efforts from 1994 to 2012 have been focused on computer modeling of flows inside MHD channels, and the overall funding and activity in MHD research has been significantly lower than in the 1970s and 1980s.

1.2 MHD Power Generation Basics

Direct Power Extraction via magnetohydrodynamics is accomplished by forcing an electrically conductive fluid though a magnetic field and connecting a circuit to the system for electrical power generation. The basic concept of an MHD generator is shown in Figure 1.

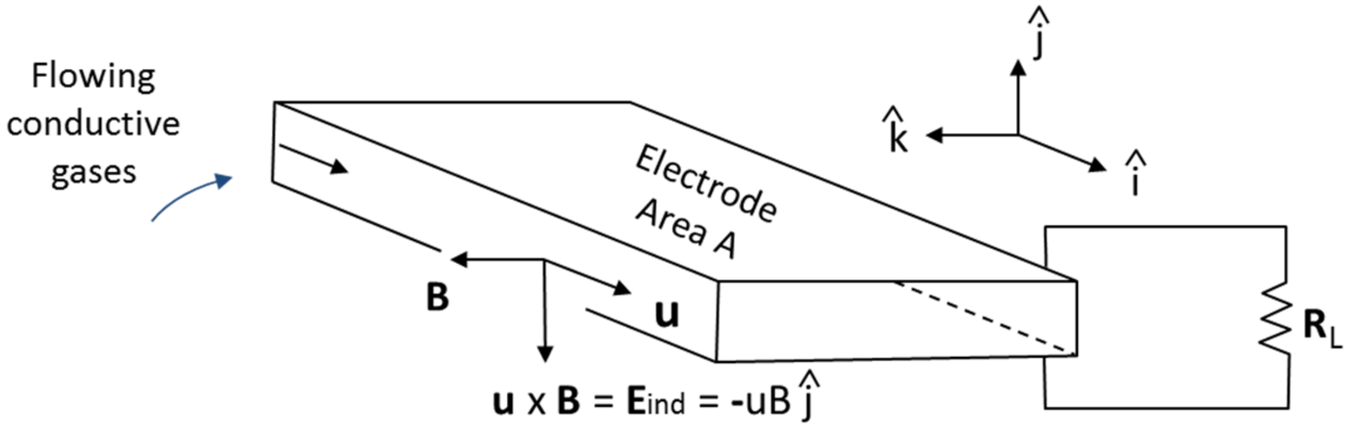

Figure 1 : Concept of a DC MHD generator. The cross product of the fluid's velocity, **u**, and applied magnetic field, **B**, leads to an induced electric field, **E**ind**.** Connecting a load, R_L, to the electrodes leads to electrical current flow in the system and in turn power generation (relation not shown).

An MHD generator essentially acts as the combination of a steam turbine and electrical generator as found in a conventional system, and is inherently simpler in that it does not require any mechanical parts. MHD generators can be configured to generate either AC or DC electricity; however existing practical AC generators require working fluids such as liquid metal which have a high electrical conductivity. DC generators can be effective with working fluids having conductivities that can be achieved in partially ionized gas flows and hence have been the focus for combustion driven systems. The governing equations for an MHD generator are presented in Table 1 of Section 2.3.

The configuration of direct power extraction via MHD has in the past been delineated to either being called an "open cycle" or "closed cycle" system. In an open cycle system the working fluid only passes through the MHD generator once, and this approach typically involves utilizing the combustion products as the working fluid. A closed cycle system passes the working fluid through the generator multiple times; essentially recycling the working fluid in a closed loop. So the closed cycle approach requires a high-temperature heat exchanger to exchange energy between the combustion product and the working fluid. In both configurations, the power output of the generator is approximately proportional to system parameters as shown in equation (1)

$$P_{out} \propto \sigma u^2 B^2 \tag{1}$$

where Pout is the output power of the MHD generator, σ is the electrical conductivity of the working fluid, u is the velocity of the working fluid, and B is the applied magnetic field strength. All three of these parameters differ considerably from what would be found in a conventional power generation system utilizing a turbine and AC generator. In the open cycle configuration, the MHD power train has in the past typically consisted of a pressurized cyclone combustor, followed by flow through a nozzle and into the MHD generator. To give a sense of parameter values, a previously designed 1000 MW_e open cycle coal system utilized a 6 Tesla superconducting magnet and a flow velocity of Mach 0.885, a temperature of 2700 Kelvin, and a pressure of 6.37 Atm. at the nozzle [13]. In addition, the combustion products were to be seeded with approximately 1 % potassium prior to the stream entering the nozzle. Seeding for MHD entails the addition of readily ionizable elements and is utilized in both open cycle and close cycle systems as it enhances the conductivity term by several orders of magnitude.

Under typical combustion-driven MHD generator conditions, in addition to the induced voltage depicted in Figure 1, the Hall Effect must also be considered. The Hall Effect leads to electrical current in the same axis the working fluid is travelling, and effectively reduces the power output from the simple generator shown in Figure 1. To get around this, the electrodes in a generator can be broken into individual segments along the length of the generator, which can nearly eliminate the adverse effect of the Hall current. Such a generator can be called a linear segmented Faraday generator. In contrast, a generator can also intentionally utilize the Hall current to generate power, and hence is called a Hall generator. In this configuration, the paired electrodes are short circuited which leads to maximum current in the axial direction of the generator. The idealized circuits for the segmented Faraday versus Hall MHD generator are shown in Figure 2.

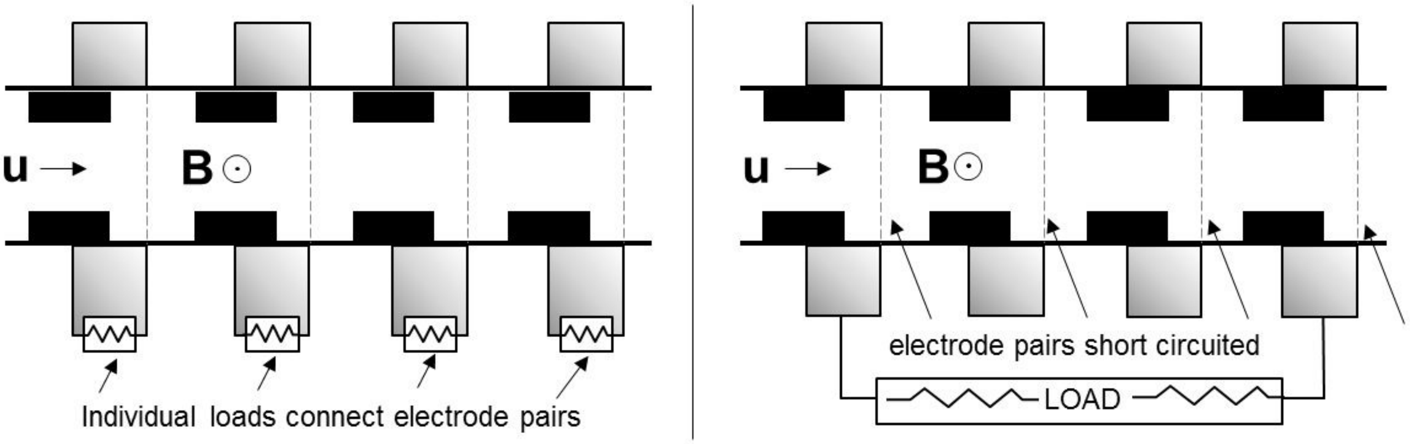

Figure 2 : Ideal load connections for a Faraday MHD generator (left) and Hall MHD generator (right). The magnetic field B is pointing out of the page. Electrodes (dark black) shown protruding into the channel would be separated by insulating material to create a smooth channel wall.

In addition to the circuit loading variations needed for Hall versus Faraday based power extraction, there are geometric variations of the generator. A segmented linear channel with a rectangular cross section was the preferred geometry during the DOE's program in the 1980s and early 90s, whereas disc shaped geometry has been preferred in the more recent Japanese program. There are numerous advantages and disadvantages inherent to the different loading and geometric shapes possible, and Messerle provides a good overview along with the relevant equations to analytically predict power out for the various configurations [14].

Lastly, the MHD cycle is primarily suited for use as a high temperature cycle and so can be expected to be implemented as part of a combined cycle power system. For example, the MHD generator as a topping unit integrated with a traditional Rankine steam cycle. In the above mentioned 1000MW$_e$ system, the MHD topping cycle was designed to achieve 23.5% enthalpy extraction on top of a supercritical bottom cycle having an efficiency of 40%. When considering the losses and auxiliary power requirements, this lead to a reported combined cycle plant with an HHV thermal efficiency of 43.7% [13]. It is worth noting one of the prior shortcomings of the open cycle MHD steam plant was the need for very large systems to demonstrate high efficiencies. Considering this, as well as unspectacular performance predictions for what was expected to first be deployed, it is not surprising that MHD did not make the jump to commercial success in the 1990s. However, it is worth noting that during the previous MHD research it was thought that a mature commercial coal-fired MHD steam combined-cycle plant could yield HHV thermal efficiency of up to 60% [15].

Also noteworthy is the aforementioned 1984 1000MW$_e$ open cycle design includes an ASU. Hence, the most expensive component of the oxy-fuel approach to carbon capture is already inherent to that system. There will be some modifications to make the system fully carbon-capturing, for example costs and equipment associated with compression of the carbon dioxide flue gases for storage and transport. Still, this apparent synergy between the past open cycle MHD approach and today's oxy-combustion for carbon dioxide capture warrants further investigation. However, whether the open cycle MHD approach makes the most sense in terms of system performance and reliability remains to be seen.

2. Scope of Effort and Initial Findings

As evident in the preceding sections, there is a wealth of prior knowledge on the subject of MHD power. This information was largely obtained in the pre-digital era. Currently, we are in the process of digitizing a large volume of MHD reports discovered in NETL archives with plans to make them available. We would also like to make the 35 editions of Proceedings from the Society of Engineering Aspects of Magnetohydrodynamics (SEAM) covering 1961 to 1996 more readily available to the public, and are evaluating copyright issues to be able to do this. Given the volume of information to go through, as well as a number of MHD power approaches that might be considered, our initial research efforts are largely generic: i.e. efforts that would be applicable to a wide range of MHD power scenarios that might be viable. In particular, we discuss key parameters and technical issues that have changed since DOE's legacy MHD program, as well as our effort to develop a high temperature combustion modeling computational tool, our effort to develop a multi-physics CFD model of an MHD generator, and our effort to build a computational based description of MHD boundary conditions.

2.1 Evaluation of MHD Power: What are the issues and what has changed in 20+ years?

As previously mentioned, MHD technology for power generation from coal is already proven as a concept, but MHD funding was terminated in the 1990s due to the high cost of designing, constructing, and operating a complete MHD-steam plant [6]. Besides the unfavorable economics, the MHD concept did have some remaining technical issues to be addressed. A 1993 government report [6] cites five "potential problem areas and concerns" of coal MHD technology;

1) Slag removal problems

2) Channel operation problems
3) Concerns about the cost-effectiveness of seed regeneration process
4) Uncertainties in fully integrating MHD systems
5) Uncertainties in Scaling Up MHD Systems

We discuss each of these problems at various lengths, and discuss what has changed in the last 20 years that may lessen these concerns, or develop completely new approaches that avoid these problems altogether.

2.1.1 Slag removal problems

According to a paper published by TRW engineers on the $50MW_t$ slagging combustor utilized at the CDIF, the nominal slag recovery was 58%, with 65% being retained during long duration testing [16]. Examining the experimental data, most of the lower retention values appear to be during start-up and "flow stabilization" periods. Further, during stable flow conditions the slag retention was quite high-exceeding 70% for 5 hours of stable flow during testing. Lastly, it is notable that the TRW engineers claim the design called for 60% retention so in their view the slag retention of the combustor largely met the expected criteria.

The issue of seed absorption by slag and subsequent reduction in conductivity at the CDIF [6] is not mentioned in the TRW paper. The authors do discuss a slightly lower than expected measured conductivity in the MHD generator at the CDIF, but they attribute this to "pre-combustor performance and second stage mixing/combustion characteristics not optimized". In the literature, there are earlier mentions of seed entrainment in slag within the combustor [17]. But the use of a second stage within the combustor was developed so as to inject seed subsequent to slag removal which was an approach to mitigate this. The unit at the CDIF was a two stage combustor. Also, at this time we are unable to find experimental data whereby ash not retained in the combustor enters the generator and lowers the plasma conductivity. Indeed, earlier experiments to validate conductivity expectations suggest that the presence of ash may actually slightly increase conductivity when plasma temperature and seed concentrations are kept the same [18]. On the relation between slag not being retained in the combustor and downstream plasma conductivity in the MHD generator, there appears to be some discrepancy between reports suggesting that this would be an important topic for study in future investigations.

In the directly fired coal open cycle scenario the presence and interaction of slag with materials of construction will remain an issue to contend with. There are two factors which can be expected to be adversely effected by slag not being retained in the combustor 1) lower slag retention means more slag material to separate from seed material downstream as part of a seed recycle process and 2) lower slag retention would likely lead to more deposits in the generator which could adversely affect electrical current paths in addition to creating additional heat losses by increasing the resistance across the MHD channel. Incidentally, it is worth noting that coal slag can be expected to have electrical conductivity in the range of 1 to 5 S/m, and conservatively estimated as being 15 S/m when accounting for slag polarization [13]. These values are in the ballpark of the partially ionized gas stream's conductivity from which power is being extracted; thus having a layer of slag bridging segmented electrodes is not that much of an issue. Indeed, such generators are intended to operate with a protective layer of slag. Overall, the slag retention issue is important, as lack of retention exacerbates problems #2 and #3.

2.1.2 Channel Operation Problems

The electrodes at CDIF were made of copper, as water cooled metallic electrodes became the material of choice for coal MHD due to the lack of any available hot ceramic-type electrodes which could withstand the electro-chemical attack within the MHD generator [19]. Platinum caps were used to protect the copper. The caps must be able to withstand some degree of electrical arcing, which is a particular problem metallic electrodes face in MHD channels, and platinum shows a desirable arc resistance [20].

Tests in the CDIF generator revealed problems with the platinum caps lifting from the copper on about 100 of the 2500 total electrode segments found after an initial shutdown inspection [6]. Platinum has a thermal expansion of about half that of copper which means there is a thermal expansion mismatch, so it is conceivable the issue might be alleviated by tailoring alloys to create a better thermal expansion match between electrodes and caps. Looking into improving the method of attaching the caps to the electrodes could also be a solution. However, it may be more useful to look at approaches that prevent destructive arcing from occurring in the first place, or at least to mitigate the issue.

Today, there may be a way to mitigate the arcing issue by using advances in high speed solid state electronics and computer technology, with active impedance control to each individual electrode segment load. Such a concept wasn't available before as an option, but in fact was mentioned in earlier work as a potential future solution to the problem of arcing [21]. Depending on the reason for arcing, this could prove effective as the voltage to initiate an arc is greater than the voltage to sustain an arc. In addition, there are new measurement techniques which could be utilized to visualize the locations of the arcs within the generator to better understand the phenomenon of arc-electrode interaction [22], [23].

The arcing phenomenon was exacerbated by the use of water cooled metallic electrodes. In particular, positive potassium ions from the flow could diffuse through the slag layer making contact with the cathode electrode. Once at the cathode, the ions are neutralized and a metallic potassium layer can form causing leakage across electrode segments and "grouping" of the segments. At the gap between the newly formed electrode segment groups, the axial hall field can be exceeded, leading to electrode arcing and damage [19]. The possible solutions are 1) find a higher temperature electrode system that works for coal or 2) eliminate the slagging generator approach entirely.

With respect to high temperature ceramics that resist degradation from coal slag, progress has been made in the last 20 years for coal gasifier technology. For instance, NETL's Aurex 95P material has exhibited up to a 50% increase in service life in slagging conditions as compared to previously utilized chromia-alumina refractory materials [24]. The focus for this type of refractory development has been to limit slag penetration, in the case of Aurex 95P by taking advantage of a slag reaction to phosphorous pentoxide within the refractory [25]. For MHD, electrodes in a "clean" MHD generator, such as those used in a natural gas driven facilities operated in the USSR's U25 facility , were largely zirconia-based ceramic materials [21]. Still, some of the approaches to limiting slag penetration for gasifiers materials could conceivably be adapted to ceramic electrodes that also have the desirable electrical properties for MHD power.

The other approach to dealing with MHD channel degradation from the coal slag is to simply move to a non-slagging generator. The closed cycle approach completely decouples the combustion gases and slag from the working fluid. The additional benefit here is the use of non-equilibrium plasmas which yield a higher electrical conductivity and in turn can be more practical then the open cycle approach at a smaller scale. The draw back to the close cycle approach is the need for a high temperature heat exchanger and the less direct use of the potential of the combustion process to generate useful work. Still, all these approaches should be left on the table until a thorough evaluation of all the trade-offs is performed. It is, however, encouraging that there are a number of possible approaches available that could alleviate channel problems encountered before or eliminate them entirely.

2.1.3 Concerns about the cost-effectiveness of seed regeneration process

Although the seed regeneration system developed by TRW and deployed at the CDIF was a technical success, the process was thought to be too expensive. Specifically, an estimate is provided that says that the seed regeneration might require more than 20 percent of the average sales price of the electricity generated by the system [6]. It is worth noting that the pollutant that was being focused on during the past MHD effort was sulfur - thus many cost estimates consider the baseline as a plant that had no sulfur control. In an MHD system, the potassium seed functioned as the sulfur control in addition to enhancing the conductivity. So the system had an inherent advantage to tackling the pollutant of concern at the time. Likewise, MHD can require an ASU which can also be used to produce near pure CO2, and hence also has an inherent advantage as a carbon capture route. Thus, we plan in the current study to evaluate cost increases associated with adding carbon capture, compared to accepted baselines in other NETL studies [3]. In TRW's process, potassium carbonate was injected in the system upstream of the generator and the potassium would react with the sulfur downstream of the generator and form potassium sulfate. This potassium sulfate was then processed to recover the potassium and reform as potassium carbonate for re-use. By performing this function, the cost of seeding was offset by the savings realized through not having to install a process aimed at Flue Gas Desulfurization (FGD) [26]. In the context of carbon capture, seed recovery and regeneration might also be integrated into a process for flue gas clean-up, heat recovery, and carbon dioxide compression such as NETL's Integrated Pollutant Removal (IPR®) process [27]. Additionally, an approach that differs from TRW's regeneration approach that could be promising because of a synergy with CO_2 capture is seen in the University of Tennessee Space Institute (UTSI) weak-base resin process for seed regeneration developed during prior MHD research. This process uses CO_2 under pressure (50 to 100 psig) to prepare/regenerate commercially-supplied ion-exchange resin to accept sulfates from spent-seed solution [28].

At this point, it is clear there are enough differences both in possible synergies with CO_2 capture, as well as differences in what we consider as power plant baseline pollutant controls to expect changes to the seed recovery approach. Even if potassium carbonate remains the seed of choice and something similar to TRW's process is used, the costs for this may be favorable as such a power plant would not need FGD and as it can instead rely on the seed regeneration process to capture sulfur.

2.1.4 Uncertainties in fully integrating MHD systems and Uncertainties in Scaling Up MHD Systems

The DOE's POC program divided the MHD steam plant topping unit and bottom unit development to the CDIF in Montana, and the University of Tennessee Space Institute in Tennessee, respectively. So a completely integrated combined cycle has not been demonstrated in the United States to date. Thus, there could be unforeseen problems in the integration. The components that have been tested are also much smaller than commercial scale, and so unforeseen scale up problems could arise. Since neither of these concerns entails specifics, there is nothing specific to address at this time. Unforeseen scaling and system integration issues are encountered in many technological problems, and certainly MHD will be no different. With respect to system integration, a particular issue that needs to be examined is the need for cooling water to the MHD topping unit and how this can best be integrated into use as boiler feed water heating.

2.1.5 Modernized MHD power train system parameters

As can be seen in equation (1), the MHD generator parameters we are primarily interested with respect to power output are electrical conductivity of the working fluid, the velocity of the working fluid, and the applied magnetic field.

The electrical conductivity is affected by the temperature and pressure of the working fluid, generally increasing with increasing temperature and decreasing with increasing pressure in non-linear relationships. The type of seed and concentration of seed also impacts the conductivity. In legacy work, potassium was determined to be the most logical seed choice due to its availability as well as low ionization potential [21]. Maximum conductivity in typical MHD conditions is obtained with 0.5 to 3 % molar weight of seed material added to the working fluid in the open cycle approach. Currently, there isn't any apparent opportunity to significantly improve on earlier generator performance through changes in seed.

The temperatures we might work with, on the other hand, appear to provide some opportunity to improve generator performance. This is due to the fact that in previous efforts enhanced oxygen combustion was utilized, for example 32% oxygen enrichment [13], rather than oxy-combustion. Producing oxygen requires energy, and at increasing oxygen levels the conversion of chemical energy to thermal energy has dimensioning returns because of chemical dissociation of the combustion products as well as heat losses through the power train. So the level of enrichment could be optimized based on these considerations as well as the energy costs of producing that oxygen [21]. With oxy-fuel for carbon capture, there is the opportunity to burn with much higher oxygen concentrations than before which can result in even higher temperatures. From available plasma temperature and conductivity data [21], it can be estimated that combustion temperatures could be increased by around 300K, resulting in a factor of about 3 improvement in conductivity and in turn the same power output improvement factor for the open-cycle approach. However, as previously mentioned heat losses must also be considered which would reduce this. Additionally, pre-heating of the oxidant was in the past elevated, for example to 1200 ˚F [13]. So there may be safety issues to overcome to significantly pre-heat gasses having higher concentrations of oxygen. Lastly, there is limited data on effective flame temperatures in large scale systems combusting pulverized coal with higher oxygen concentrations. Regarding the last point, efforts are currently underway to characterize properties of high temperature coal flames which will in turn inform computational models for high temperature burner design [29].

On the economics of the ASU, the energy requirement cited in 1988 for a self-contained ASU was 300 kW/tO_2 [15]. Today, current state of the art cryogenic separation processes can be expected to consume 200 kWh/tO_2 [3], with a theoretical minimum of 47.82 kWh/tO_2 indicting there is room for further improvement [3]. The main point is the energy costs associated with mature oxygen separation technologies have seen a dramatic decrease in costs over the last 20 years, and this is a major development in support of revisiting MHD power. Even without carbon capture as a motivation, we would expect the optimal level of O_2 enrichment for open cycle MHD power to be different from before because of this price decline.

The velocity parameter also has room for improvement, provided flow instabilities when the flow exits or enters the transition areas (e.g. nozzle and diffuser) can be avoided. Increasing the combustion pressures can enable even higher velocities, but as previously noted increased pressure is not desirable in the generator as it reduces the conductivity term.

The magnets utilized during past MHD efforts have continued to be developed over the last 20 years, in particular superconducting magnet technology. Specifically, efforts to improve these systems have been developed and deployed in the large Hadron Supercollider and the ITER fusion reactor. Whereas previously 6 Tesla superconducting magnets were envisioned for commercial systems [17], now titanium-niobium superconducting magnet systems are commercially available with strengths of 9 Tesla. Niobium-tin based systems are available in even higher strengths, but are also more expensive. Since the MHD generator's power output is proportional to B^2, the availability of higher strength superconducting magnets seems to be a significant development. There are a couple of caveats associated with this. First, for a segmented Faraday type generator there will be increasing concern about exceeding the hall breakdown voltage across the insulation which separates the electrode segments. So the insulation thickness and properties may have to be modified, which could reduce some of the advantage of the higher strength magnets. Second, the higher costs of higher strength magnets necessitate an involved system optimization analysis of costs as was done in earlier research [30]. Pertinent to efficient power generation, superconducting magnets require cooling such as liquid helium which costs energy to produce. A related development in the last 20 years or so is the introduction of high temperature superconducting magnets. For example, the BISCO type superconducting magnets can be cooled by liquid nitrogen which a cryogenic based ASU could provide. So these magnet systems would seemingly be worth considering, even if the magnets aren't as strong as the liquid helium cooled varieties. There have been tremendous advanced both in the strength and variety of superconducting magnets over the last 20 years, and this strongly supports revisiting MHD Power as a viability technology.

Perhaps the most dramatic technological improvement since previous MHD efforts is in the area of computational modeling. Previously, generators were designed from empirical models which were largely one-dimensional. Today, we have three dimensional multi-physics models that can potentially be utilized to design a more effective MHD power train. There is significant effort needed to produce these advanced models, but the potential return (as seen in other technical applications) makes this a promising approach.

2.2 Combustion Modeling

To begin addressing the combustion issue, current work applies transported probability density function methods to solve high-temperature combustion problems. The CFD model framework is in the OpenFOAM platform, with the eventual goal of integrating it with a CFD model of an MHD generator.

One modeling focus has been the combustor, upstream of the MHD generator. There the emphasis is on multiphase turbulent combustion and radiation modeling for oxy-coal combustion. The environment differs from that of a conventional air-coal combustor in two important ways: high temperatures (~3000 K), and high concentrations of radiatively participating molecular species (especially CO_2 and H_2O), in addition to coal particles and soot. The models are being developed using elements from the OpenFOAM toolbox [31] as the underlying CFD solver.

It is anticipated that turbulent fluctuations in composition and temperature, and complex interactions among turbulence, gas-phase chemistry, solid-phase coal and soot, and radiation will be important in this combustion environment. For that reason, a transported composition probability density function (PDF) method has been adopted as the basis for the turbulent combustion modeling, where a stochastic Lagrangian particle method is used to solve a modeled transport equation for the joint PDF of species mass fractions and mixture specific enthalpy. PDF methods have proven to be particularly effective for dealing with turbulence-chemistry interactions in flames [32, 33]. The PDF method is coupled with a stochastic photon Monte Carlo (PMC) method for radiative heat transfer that maintains essentially line-by-line spectral accuracy [34]. The coupled PDF/PMC model then fully accounts for turbulence-chemistry-radiation interactions, and when combined with a soot model, for turbulence-chemistry-soot-radiation interactions, in both Reynolds-averaged [35,36] and large-eddy simulations [37].

A systematic hierarchical approach has been pursued for model development. First, simulations were performed for laboratory syngas ($CO/H_2/N_2$)-air jet flames where detailed experimental measurements are available [38], to implement and test the PDF/PMC models in a combustion environment that is similar to that encountered in oxy-fuel systems. Excellent agreement with experiment was realized for syngas flames [39]. The next step was to simulate an oxy-natural gas system where the environment is as close as possible to that in an oxy-coal system, without the complications of a solid fuel. Key criteria for selecting an experimental configuration included the absence of flue-gas recirculation and wall cooling (to maintain high temperatures), and the availability of high-quality temperature and other measurements. For this purpose, a 0.8 MW oxy-natural gas burner was selected [40]. Available experimental data include profiles of mean velocity, temperature and major species. At the time of this writing, a parametric study on the influence of the chemical mechanism and the radiation models on computed results is nearing completion. Examples of comparisons between the baseline model and experiment are provided in Figure 3. The level of agreement is at least as good as any that has been reported earlier in the literature for this configuration.

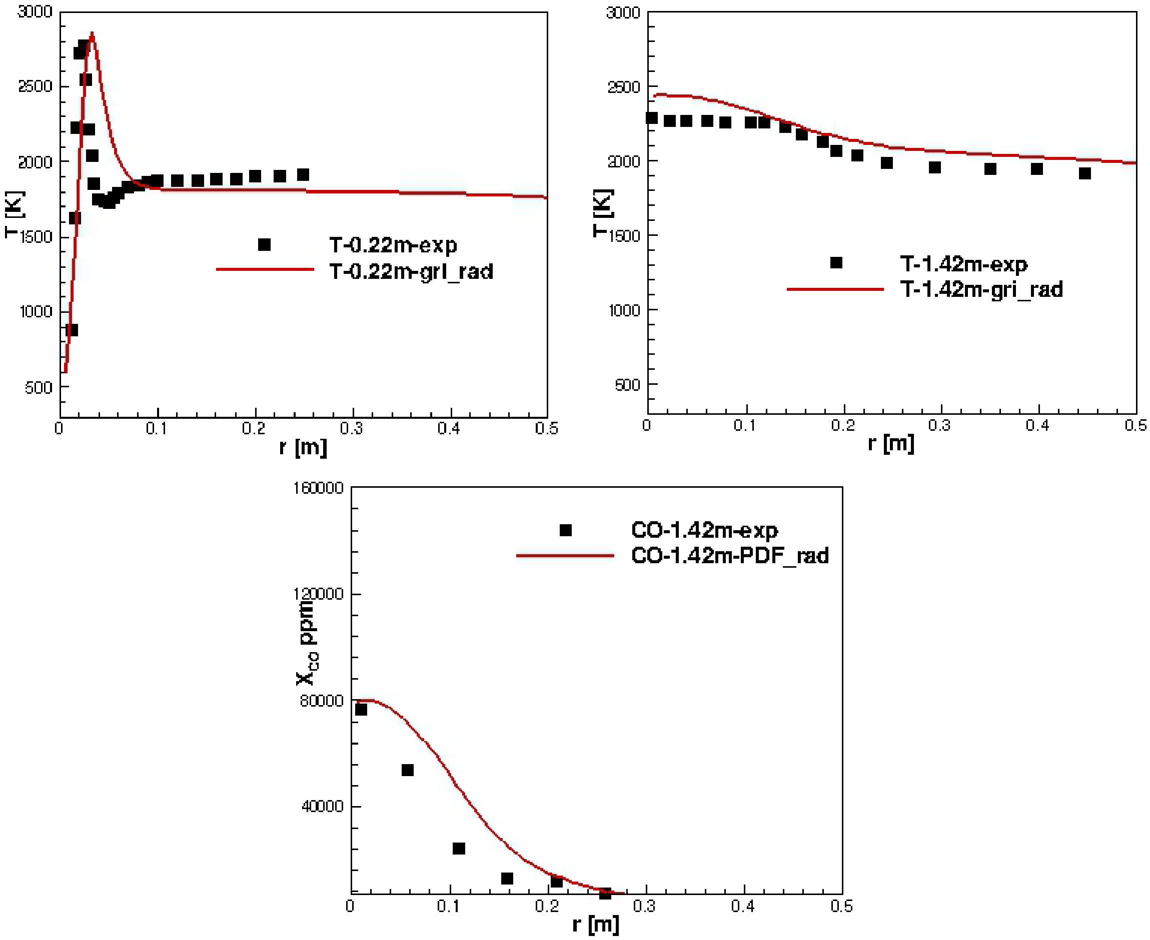

Figure 3 : Computed and measured [40] mean temperature and mean CO mole fraction profiles at specified axial locations (*x*) downstream of the fuel nozzle a) Mean temperature at *x* = 0.22 m. b) Mean temperature at *x* = 1.42 m. c) Mean CO at *x* = 1.42 m.

The next step will be to add inert solid particles and swirl, and to compare with experiment for a benchmark configuration [41]. Then coal combustion will be addressed.

2.3 CFD Simulations of the MHD Generation Channel

We are currently validating an MHD generation channel solver which has been developed by combining and extending several solvers which are distributed with the OpenFOAM library [31, 42] based on our previous experience of modifying OpenFOAM to simulate flame plasmas [43]. The set of equations which we have used to calculate the performance of an MHD generation channel is similar to the set of equations used by Ishikwa et al. [44, 45]. The model consists of a set of conservation equations for the bulk fluid and a charge conservation equation for electric field these are summarized in Table I.

Table I – Governing Equations	
Mass	$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\rho u\right)=0$
Momentum	$\frac{\partial \rho u}{\partial t}+\nabla\cdot\left(\rho uu\right)+\nabla p=\nabla\cdot\left(\tau\right)+\underbrace{\vec{J}\times\vec{B}}$
Energy	$\frac{\partial \rho H}{\partial t}+\nabla\cdot\left(\rho uH\right)=\frac{\partial p}{\partial t}-\nabla\cdot\left(q\right)+\underbrace{\nabla\cdot\left(u\cdot\tau\right)}+\underbrace{\vec{J}\cdot\vec{E}}$
Charge (Ohm's Law)	$\nabla\cdot\vec{J}=0$
Current	$\vec{J}=\sigma\left(\vec{E}+\vec{u}\times\vec{B}\right)-\frac{\beta}{\lvert\vec{B}\rvert}\vec{J}\times\vec{B}$
Generalized Ohm's Law	$\nabla\cdot\left(\sigma_{eff}\nabla\phi\right)=\nabla\cdot\left(\sigma_{eff}\left(\vec{u}\times\vec{B}\right)\right)$

The temporally constant, but spatially non-uniform, magnetic field is assumed to be sufficient in magnitude that induced magnetic field is negligible. In contrast to the model of Ishikawa et al. [45], the magnetic field can have arbitrary direction and the electric field is in general three-dimensional. Ishikawa et. al.[45] neglected variations in the electric potential in the direction parallel to the magnetic field. The conductivity and Hall parameters are treated as material properties of the fluid which are functions of temperature. Conservation of mass, momentum and energy are used to describe the flow supplemented by the ideal gas equation and additional equations to describe un-resolved turbulent motions.

The baseline for one version of the solver is a "density-based" compressible solver, (*rhoCentralFoam [46]*) with an Ohm's law solver, *electrostaticFoam*. A second version replaces the density based solver with a flow solver *(rhoPimpleFoam)* which use a segregated pressure-correction (PISO-SIMPLE) algorithm. The baseline flow solvers use slightly different methods to spatially discretize the bulk flow mass momentum and energy equation. From these baselines, the solvers were extended by adding the Lorenz force to the momentum equation, "Joule" power source to the energy equation and in the case of the pressure-based solver a stress-work term to the energy equation. The Ohm's law solver was modified to use a tensor conductivity similar to what has been proposed by Gaitonde [47] and Parent et. al. [48]. We have found the each flow solver has advantages and disadvantages, which have been reported in literature [49, 50, 51]. Our initial tests have shown that the density based solver excessively dissipates shear and entropy waves causing errors in the predicted boundary layer thickness leading to inaccurate prediction in drag and heat flux. On the other hand, the segregated solver which uses 4th-order pressure dissipation tends to dissipate to shocks more than the density-based solver. Our current preference is the pressure-based model which overall has less numerical dissipation due to the implicit discretization of pressure. It also allows for time-steps of the order of the convective time-scale versus the acoustic time scale. This has a large impact on convergence rate with respect to wall-clock time, since as the mesh is refined in the wall-normal direction, the difference between the acoustic and convective time-scales can become fairly large. In the future we plan to improve the flow solver to combining the desirable properties of both these flow solvers.

For system validation targets, we have initially selected the "Sakhalin" segmented linear generator channel [52] and radial generator experiment from the Tokyo Institute of Technology [53]. These studies are desirable because of the availability of previous simulations [44, 45, 54] in addition to experimental measurements. The generation channel of the "Sakhalin" is 4.5m long, with a cross section which is 0.9m x 1.0 m at the inlet and increases to 1.6m x 1.0m at the outlet. The nominal power of the system is 510 MWe. The simulations also include a supersonic nozzle section upstream of the channel and the diffuser downstream of the channel. The "Tokyo" radial generator is a much smaller unit. The generation channel is 12mm wide at the inlet and 16 mm wide at the exit and extends from 47.5 to 80 mm. Both experiments were performed under pulsed conditions, but we will approximate the operating as steady in the simulations. Table II summarizes the key characteristics of the two systems. Initial results from simulations are shown in Figure 4.

Table II - Operating Parameters of Validation Targets

	Sakhalin	Tokyo Institute of Technology
Type	Faraday, linear	Hall, disc
Power	510 MWe	200 kWe
Mach #	2.4 (est)	2
Voltage Drop	2.5 kV	100 V
Magnetic Field Strength	2T	4T
Electrical Conductivity	50 S/m	600 S/m
Hall Parameter	0.5	9.5
Gas Temperature	2750K	2150K
Pressure	0.15-0.35 MPa	0.13-0.2 MPa

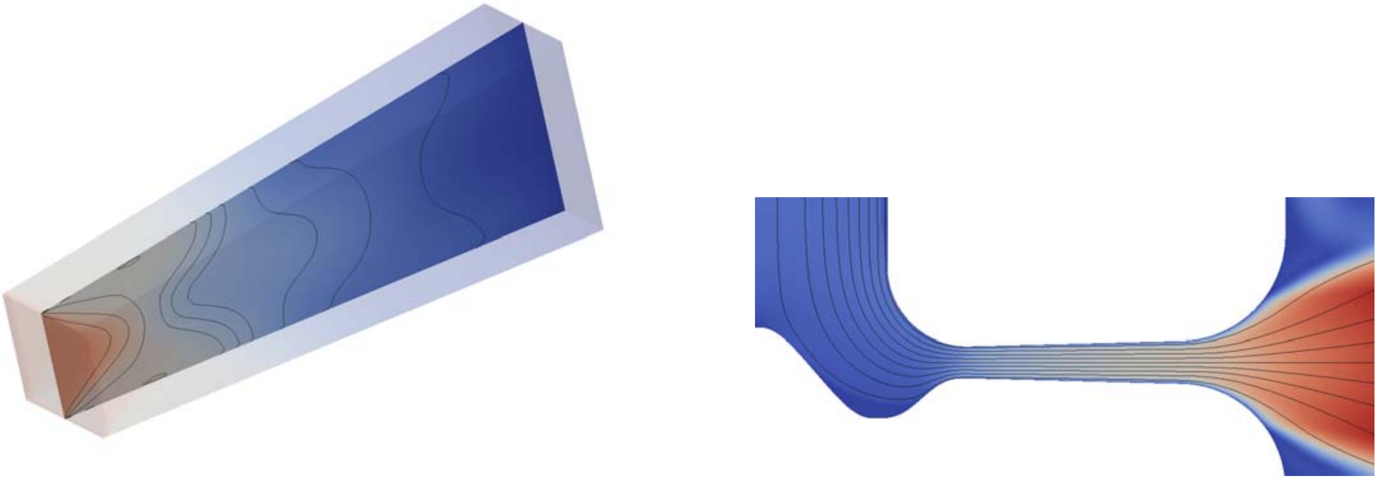

Figure 4 : Simulation results using the pressured-based solver: (left) Sakhalin linear generation channel [49]. Pressure contours are shown. (Red ~3.3 bar, Blue ~1.4 bar) (right) Tokyo Institute of Technology radial generation channel [50]. Mach number contours and streamlines are shown (Red Ma = 4.4, Blue Ma = 0). Flow is from left to right. The incoming flow is accelerated to Ma = 1.0 at the throat and further accelerates in the divergent supersonic nozzle due to the outlet pressure being lower than the 1st critical point.

2.4 MHD Channel Flow and Wall Functions

The modeling efforts also address issues in using wall functions to bridge the laminar sublayer to the fully turbulent boundary layer when Lorentz force is dominant or equally important as compared to other forces. In order to accurately predict phenomena in a magnetohydrodynamic (MHD) power generation channel it is necessary to quantify the effect of the electromagnetic forces on turbulent flow. In current engineering practice, Reynolds Averaged Navier-Stokes (RANS) simulations are extensively used because they are less demanding in terms of computational resources but their validity is limited by the closure models describing turbulence and the mean flow close to the wall. In order to improve the accuracy of the turbulence models used in RANS simulations this study is focused on development of appropriate wall functions for turbulent flow simulations under electromagnetic forces.

The fluid flow in MHD applications is turbulent and usually compressible. The flows involved in MHD power generation are described by the electro-magnetic field equations coupled with the energy, and Navier-Stokes equations. In this study, an order of magnitude analysis was performed to simplify the governing equations and hence computational time. The reduced equations represent flow through two parallel walls. The fully resolved (i.e. down to the wall $y^+ \sim 1.0$) flow from the simplified equations along with DNS (direct numerical simulation), LES (large eddy simulation) and experimental data from the literature will be used to formulate accurate wall functions to be used in RANS simulations of MHD flows.

The approach is divided into three stages; simulation of turbulent incompressible flow, simulation of turbulent compressible flow, and finally prediction of the turbulent compressible flow coupled with electromagnetic forces. A pseudo two dimensional model is being developed to predict MHD flow between two parallel plates. The model accurately predicts the mean velocity profiles for turbulent incompressible flow. It also predicts the influence of the Prandtl number on the mean velocity and temperature profiles. Some results from predictions of turbulent compressible flow are shown in Figure 5 a) and b). These results show the effect of the wall heat flux on the mean velocity and temperature profiles.

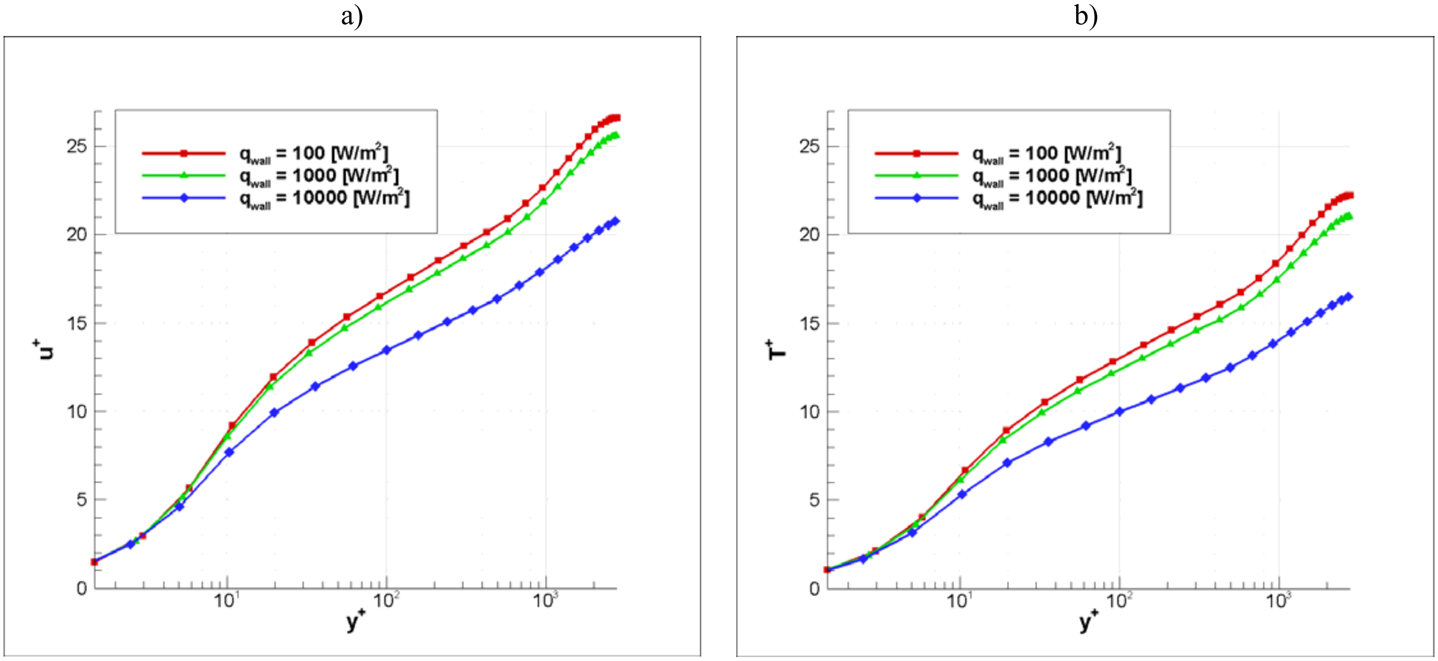

Figure 5 : a) Mean Velocity, and b) Mean Temperature Profiles of a Turbulent Compressible Non-Adiabatic Flow.

The model is being extended to include the electromagnetic effects. Predictions of the turbulent MHD flow between parallel plates will be evaluated against data available in the literature. If necessary the numeric models for the electromagnetic phenomena and electromagnetic field flow interactions will be refined or expanded. For example, the Lorentz force arising from the interactions of velocity field with electromagnetic field acts as a body force in the momentum equations similar to the gravitational field. The direction and magnitude of this force can be modulated to extract maximum benefit from MHD generator. The resulting wall functions will be particularly useful for RANS simulations of MHD flows in general.

3. Conclusion

Based on our initial assessments, a revisiting of MHD Power technology appears worth further effort and investigation. By utilizing an Air Separation Unit, the direct power extraction via MHD approach appears to be synergistic with the oxy-fuel approach for carbon capture. Even better, this approach could conceivably yield a higher thermal efficiency coal plant then a conventional steam plant without carbon capture. This would lessen the economic burden of adopting carbon capture, and in turn expedite the transition to lower greenhouse gas emissions from the power generation sector. In light of the potential favorability of the approach, NETL has initiated research including a literature review of legacy MHD Power efforts, advanced high temperature combustion modeling, MHD generator modeling, and MHD boundary condition formulation in support of those models. Additionally, we plan to imitate a formal techno-economic analysis of direct power extraction in the 2013 fiscal year. This analysis will yield specific numbers on performance and costs of oxy-combustion driven direct power extraction.

In the last 20 years, advances in combustion and superconducting magnet technology have been realized which can increase the performance of the combustion driven MHD power train. Further, technical issues encountered during past efforts could be mitigated or avoided entirely though new approaches. A new approach already in development at the NETL-RUA is the application of advanced CFD modeling to MHD power application. A transported composition probability density function (PDF) method coupled to a stochastic photon Monte Carlo (PMC) method was applied to a high temperature gas combustion problem with good agreement to experimental results. Moving forward, we will add inert solid particles and swirl to the model, and generally work toward increasing the complexity of the modeling environment to approach conditions expected in high temperature coal combustion systems. Some preliminary CFD results from modeling two types of MHD generators were presented. Currently, we are working on improving this modeling capability. Further development will also allow model application to more complicated generator electrode loading scenarios such as those found in segmented Faraday generators. Some formulations to describe MHD boundary conditions in the channel were presented. Moving forward, electromagnetic effects will be incorporated into these models.

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