Issue Paper /

Borehole Heat Exchangers – Addressing the Application Gap with Groundwater Science

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Abstract

Hydrogeologists and mechanical engineers approach the design of geoexchange systems, and the associated borehole heat exchanger (BHE) fields, in different ways, each focusing on their knowledge areas. While these differences have created a strong research base, with well published innovations and designs that collectively allow for sustainable systems, industry has not embraced these recent advancements. Despite abundant research demonstrating how complex shallow groundwater flow and temperature conditions can influence BHE design and operation, the low temperature geothermal industry remains largely fixed on simple analytical codes and assumed uniform ground conditions. Geoexchange system inefficiencies become masked via reduced heat pump performance and increased electricity consumption. Similarly, interactions between BHE fields and infrastructure in urban areas are slow to manifest and are often unrealized due to a lack of field temperature data. While regulations that include hydrogeological factors have been developed in some jurisdictions, they are largely voluntary or rudimentary and can be unapplied in industry. Addressing this application gap may be unreasonable as designing and installing thermally efficient geoexchange systems can put them out of the cost envelope of competing heating and cooling systems. Perhaps for hydrogeologists the way forward lies in the use of BHE's to facilitate contaminated sites remediation, an area we are familiar with, and one that allows for innovative technologies to reduce cost envelopes. Following that path, hydrogeologists can help improve system efficiencies while fully considering the dynamic nature of advective and thermal transport by groundwater.

Introduction

Closed loop vertical ground coupled heat pumps (GCHPs) are considered one of the most efficient solutions for heating and cooling buildings (Fossa and Rolando 2015). GCHPs systems are also known as ground source heat pumps (GSHPs) or geoexchange systems and make use of borehole heat exchangers (BHEs) where the energy exchanging fluid is circulated in a vertical closed loop installed in a borehole. For larger building applications, the BHEs are normally arranged in "fields" that form simple arrays of interconnected BHEs. Although geoexchange systems can be considered very efficient on design, negative performance issues often arise after years of operation. Florea et al. (2017) describe two of the largest GCHP systems in the U.S., and the associated groundwater and performance issues (Ball State University 3600 BHEs and the Epic Campus 6000 BHEs). While many systems are designed for balanced ground loads (winter heat taken from the ground = summer heat return to the ground), this is often not the case in operation as most larger buildings are cooling dominated, and in some countries BHEs are only used in heating modes. One of the most important issues with shallow BHE fields, typically installed to depths of approximately 100 to 200 m below the ground surface (bgs), is the cost efficiencies due to available drilling technologies. By comparison medium deep BHE fields, typically installed to depths of 200 to 1000 m bgs, require a larger upfront drilling investment, more costly design, and are likely subject to a complex regulatory environment (Welsch et al. 2016).

In recent years, the long-term operating sustainability of many GCHPs is being called into question as building initial thermal design state can change, impacting the field internal thermal stresses and causing disequilibrium. The impacts from adjacent BHE systems, fluctuating groundwater fluxes, and nearby infrastructures can further affect the system sustainability. The decline in sustainability of BHE fields is largely attributed to these systems being designed and installed essentially as an HVAC (heating, ventilation, and air conditioning) component of a GCHP, and not an integral part of a dynamic shallow groundwater system. From the mechanical engineering point of view, the goal of BHE field design is to achieve the best BHE geometry, considering land availability and drilling strategies, the minimum overall length of vertical pipes, while typically assuming pure thermal conduction and constant ground properties (Fossa and Rolando 2015). The assumption of heat conduction only and constant ground properties essentially represents the BHE system within a closed ground environment with the only time varying components coming from building loads or external systems such as cooling towers. However, the hydrogeological approach considers (if applicable) thermal conduction and advection, heterogeneous ground properties, and thermal interferences both within the borefield and downgradient borefields, infrastructure or natural features (e.g. streams). Therein lies a major problem in that little attention is given to the hydrogeology and geochemistry in BHE borefield design, as detailed by Florea et al. (2017). The industry's design standards rely on thermal response tests (TRTs) that treat the geology as homogeneous and isotropic without groundwater flow. As will be discussed later, the difference in design perspectives is significant. What we deem as the proper approach is rarely followed but integrates the two design perspectives (for example see Diersch et al. 2011b. This approach is described in more detail later under Modeling Approaches.

The application gap is largely due to a knowledge gap. It is doubtful any hydrogeologist would design building HVAC components; however, some engineers are highly involved into borefield design while making little verifications about the subsurface environment. This knowledge gap is portrayed in standard loop design software packages. They include an economic analysis with depreciation and salvage value calculations. Within the module, a 50-year straight line depreciation method for calculating the residual/salvage value for the loop field is proposed. However, it is well known to those working in hydrogeology that any borehole or well actually has abandonment and reclamation costs not considered in such economic analysis. Closed loop BHE systems are no exception. According to EPA (1997) or ANSI/CSA (2016), the basic decommissioning procedure of closed loop geothermal heat pump systems is to pump out the heat transfer fluid and seal the borehole with grout or other approved material. Ignoring these costs and assign salvage value to installed polyethylene pipe simply shows a lack of knowledge of the 'field'.

Recent Research

BHE research can be considered 'mature' given the wide spectrum of papers published in both the hydrogeological and mechanical engineering literature over the past 10 years. This statement is not one based on 'text mining' or 'machine learning', as was done in Schwartz et al. (2019) regarding the field of contaminant hydrogeology, but rather by simply reviewing the literature, and forming an opinion. In both the mechanical engineering and geosciences literature, there was a marked increase in articles published post 2010 illustrating a growing interest in low temperature geothermal energy (Figure 1). Another factor in assessing field maturity is a consideration of how far the gap is between the research literature and the application of that research. In the case of BHE, that gap is substantial and herein lies a problem.

A brief review of the depth and extent of BHE research over the past 10 years follows. Readers are referred to several recently published review papers for a more detailed assessment of the scientific literature, government regulations, and BHE utilization rates. Somogyi et al. (2016) reviewed shallow geothermal systems including both open and closed loop vertical systems with a European focus. Lund and Boyd (2016) updated their previous worldwide review (Lund et al. 2011), which summarized the use of geothermal energy for direct utilization (i.e. including heat pumps). It is clear from these reviews just how rapidly the use of low temperature geothermal energy has expanded worldwide.

As expected, hydrogeologists have done extensive work on characterizing subsurface thermal parameters. Raymond (2018) did an updated review of the assessment of subsurface thermal conductivity for geothermal applications, which follows from an earlier review paper Raymond et al. (2011). Wagner et al. (2012, 2013) and Rouleau et al. (2016) addressed one of the main weaknesses of the often used thermal response test (TRT); that the approach only considers conductive heat transfer from the BHE and all transport effects are combined in the parameters of effective thermal conductivity and borehole thermal resistance. As recognized by Chiasson et al. (2000), higher groundwater fluxes can considerably increase the effective ground thermal conductivity. Recently considerable advancement has occurred in the TRT field with the use of distributed tests with fiber optic or submersible data loggers to measure temperature at different depths and infer a thermal conductivity profile (McDaniel et al. 2018; Marquez et al. 2018). Pambou et al. (2019) alternatively used wired temperature and pressure probes to evaluate both the ground thermal conductivity profiles and groundwater fluxes. However, while the technology and supporting research are currently available to fully assess ground thermal properties and groundwater fluxes with depth, the industry standard (Kavanaugh 2001) is still to inject a constant amount of energy into the BHE, measure the temperature changes, which when analyzed with the line source theory returns an effective thermal conductivity. While the equipment and analysis can be complex for these new TRT methods (e.g. see Raymond 2018), knowing when to implement them is straight forward if one follows Ferguson (2015) who provides a simple graphic that allows one to determine if advection can impact a BHE field. Alternately, there is good agreement in the literature that groundwater fluxes over 10^{-7} ms^{-1} affects TRT results. Dehkordi and Schincariol (2014a) performed sensitivity analyzes on thermal and hydrogeological ground properties and ranked groundwater flux among the top influential factors with regards to the efficiency and impact of BHEs during operation (fluxes above 10^{-7} ms^{-1}) as well as post-operation recovery of ground temperatures (fluxes above 10^{-8} ms^{-1}). But all this requires hydrogeological expertise and the ability to assess groundwater fluxes at a given site.

Modeling Approaches

The HVAC engineering approach, often following the ASHRAE standard method (American Society of Heating, Refrigerating, and Air-Conditioning Engineers; ASHRAE 2007), simplifies subsurface heat transfer mechanisms allowing fast and accessible BHE design (Fossa and Rolando 2015), a goal that is valuable. The systems include, with this mechanical engineering approach, three main components: the building heating and cooling network, the heat pump, and GHEs (Florides and Kalogirou 2007). To account for thermal interferences (conduction based) among BHEs within a given field, the ASHRAE method applies a correction parameter known as the Temperature Penalty. Other commercial BHE design software such as GLHEPro (2007), Ground Loop Design (GLD; Thermal Dynamics, 2019) or Earth Energy Designer (EED; Buildingphysics 2020) use pre-calculated g-functions (Eskilson and Claesson 1988) to account for borehole thermal interactions. Programs such as GLHEPro and GLD use iterative analytical modeling based on building loads to determine the required length of BHE under a long-term steady state operation. As expected, these codes are mechanically focused. Detail thermal loading can be applied for the BHE field considering corrections for hybridized systems which include the use of cooling towers or surface water systems.

Ahmadfard and Bernier (2019) conduct a comprehensive review and inter-model comparison of BHE sizing and design tools routinely used in industry. The 12 numerical codes or tools are classified into five levels of complexity from those based on rules-of thumb to the most complex, which include hourly load simulations. However, complexity here is largely the ability of methods to account for variable BHE field loads, imbalanced thermal ground loading, and borehole thermal interactions simulated by heat conduction. None of the standard methods account or design for groundwater advection except through an increased effective ground thermal conductivity.

The hydrogeological approach is different and involves the use of numerical groundwater models. Hecht-Mendez et al. (2010) list 18 numerical codes suitable for advective heat transport simulations of shallow geothermal systems considering groundwater flow. The hydrogeological heat transport community got interested into BHE design over 10 years ago, obviously after mechanical engineers had already developed heat conduction approaches. Hecht-Mendez et al. (2010) evaluated the use of MT3DMS (Zheng and Wang 1999) for heat transport simulation of closed geothermal systems along with FEFLOW (Diersch et al. 2010) and SEAWAT (Langevin et al. 2008). Hecht-Mendez et al. (2013) coupled a simulation-optimization procedure with FEFLOW to strategically adjust individual BHE loads within a multiple BHE field considering groundwater flow. This approach is different from the most complex HVAC codes presented by Ahmadfard and Bernier (2019), where the loads for the entire field are adjusted. Again, this makes sense for an HVAC approach where the building is detailed but groundwater system is simplified and not considered to be active. Hydrogeologists know that this only applies to limited cases, as evidenced by Ferguson (2015). One example is Bayer et al. (2014) that extended the simulation-optimization procedure to include adjusting BHE positions within a 54 BHE field (normally a regular grid pattern is used) in addition to loading. However, groundwater flow was considered negligible at the study site (i.e. conduction only).

The BHE design approach with groundwater heat and transport codes is based on a conventional modeling process as fully covered in Anderson et al. (2015), with the addition of BHEs as conductive line sources. For example, FEFLOW includes a BHE design interface with governing flow and heat transport equations that are solved for the area surrounding the BHE; a BHE solution is coupled with the rest of the model domain through the temperatures at the borehole nodes. The BHE solution was implemented by Diersch et al. (2010, 2011a, 2011b) based on the analytical method by Eskilson and Claesson (1988) or the numerical method of Al-Khoury et al. (2005) and Al-Khoury and Bonnier (2006). Some of the attributes added to the original method are generalized formulations for BHE types, improved relationships for thermal resistances, and direct and non-iterative coupling to the three-dimensional (3D) discretized matrices of the porous media. However, a key operational difference in using a hydrogeological code to design a BHE field is the calculated BHE fluid temperature, and thus the energy exchanged, is determined from defined boundary conditions and full media properties (porous media, groundwater, BHE fluid, pipe, grout). If this energy is not sufficient, the BHE field must be redesigned and energy recomputed via a manual iterative process that can be time consuming. With HVAC codes such as GLD, building design heating and cooling loads are inputs while inlet and outlet BHE temperatures or length of BHE are outputs, which is the contrary for the hydrogeological approach implemented in FEFLOW. Available exchanger field conditions or HVAC equipment then determine if a solution is feasible and a heat pump with a coefficient of performance (COP) or Energy Efficiency Ratio (EER) in cooling mode that varies with the fluid temperature can be considered with the mechanical engineering approach. While BHE physical and fluid properties, including fluid flow rates, are similarly inputs for both FEFLOW and GLD, the ground properties and variability therein are the parameters that are handled with most differences. Figure 2 attempts to provide a simple graphic illustrating key differences between the two approaches.

Obviously, the best BHE modeling approach is to couple HVAC and hydrogeological codes (Figure 2). This can help when considering hourly building loads with variable COP heat pumps on one hand, and advective heat transfer due to groundwater flow, on the other hand. One of the earliest examples of coupling BHE design into a groundwater heat and transport model is Diersch et al. (2011b). Here the simulation code FEFLOW (Diersch et al. 2010) was coupled with TRNSYS (TRNSYS 2004; Bradley and Kummert 2005), a building systems transient simulation tool, to model a borehole thermal energy storage system (BTES) consisting of 80 BHEs in Crailsheim Germany. As the BTES was installed through an aquifer - aquitard sequence, the simulations clearly showed the important role of groundwater flow on system efficiency and reliability. However, whether due to the complexity of coupling or lack of application, recent versions of FEFLOW / TRNSYS no longer facilitate coupling. Hein et al. (2016) used a dual continuum approach, originally proposed by Al-Khoury et al. (2010), and extended by Diersch et al. (2011a,b), to model subsurface flow and heat transport and the dynamics of heat pump efficiency through the BHE. The study was simplified in that they considered ground properties as homogeneous and isotropic. They found that including surface temperatures, geothermal gradients, and groundwater flow, variables typically neglected in most analytical models, are necessary for realistic simulations. Another modeling alternative is to use the mechanical engineering approach but implement a moving heat source solution representing BHEs subject to groundwater flow (Chiasson and O'Connell 2011, Molina-Giraldo et al. 2011, Wagner et al. 2013). While this solution has been developed about 10 years ago, it is still not available in commercial software packages to design ground-coupled heat pump systems. Considering hourly building loads and groundwater flow through numerical models, for example with the TRNSYS-FEFLOW coupling, can be complex and the resulting simulation time can be long. Shorter simulation time is expected for the moving line-source solution based on analytical modeling, which represents an opportunity for industry to integrate such innovation and better design systems.

Accounting for Groundwater Flow

Fully accounting for the role of groundwater flow in BHE field design has important but varied implications depending on whether the loading is balanced, thermal storage is being designed for, or if impacts from or to adjacent systems and infrastructure are being considered. Dehkordi and Schincariol (2014a) show the importance of thermo-hydrological parameters in BHE performance and impact (i.e. off site). Thermo-hydrological parameters are those that impact the groundwater flow and heat transport, e.g. hydraulic gradient. Dehkordi et al. (2015) expanded on this for multiple BHEs where the role of groundwater advection can be more complicated due to thermal interference between boreholes. Zanchini et al. (2012) modeled one, two, and four staggered lines of infinite BHEs with unbalanced heating load and found that even a modest 6×10^{-8} ms^{-1} groundwater velocity reduces the thermal disturbance and accelerates reaching steady state conditions. Thus, while groundwater flow did not reduce the effects of hourly peak loads, it improved long-term performance. Chiasson et al. (2000)

and Zanchini et al. (2012) also showed how groundwater flow can allow unbalanced seasonal loading to be sustainable.

Thermal Management Modeling and Urban Heat Islands

While published evidence of BHE systems failing to meet design performance, or off-site impacts to or from BHE fields, is scarce, numerous studies clearly point to the declining thermal state of groundwater. Mueller et al. (2018) used multilevel temperature monitoring wells and 3D groundwater flow and heat transport models to investigate the current thermal state of four groundwater bodies in the urban area of Basel (Switzerland). Mueller et al. (2018) followed on the work of Epting et al. (2013) for Basel. Similarly, Zhu et al. (2015) used field measurements and numerical simulations to assess the urban heat island of Cologne, Germany. They found anthropogenic heat discharge has elevated the temperature of the aquifer beneath the city by more than 5° C. These findings match those of Ferguson and Woodbury (2007) for the urban heat island under Winnipeg, Canada. Part of this heat island in Winnipeg was shown to be the result of thermal pollution from low-temperature geothermal systems (Ferguson and Woodbury, 2006). Garcia-Gil et al. (2014) evaluated the thermal impact of river water recharges induced by flood events into an alluvial aquifer influenced by geothermal systems. This work illustrated how thermal management can exploit flood induced aquifer temperature changes, and the important role of changes in hydraulic gradients. These studies show how groundwater heat and transport models are required for the sustainable management of complex groundwater resources on the urban scale. However, a key limitation recognized by Mueller et al. (2018) is the lack of temperature data, especially very shallow groundwater temperature monitoring during system operation. And therein lies one of the most difficult aspects of proving the degree of thermal interactions occurring in urban environments and failures of BHEs. From an HVAC perspective, a system just becomes less efficient than was designed for and the system is abandoned, simply expanded, or effectively becomes an electricity dominant heating system as the heat pump COP or EER drops. From a hydrogeology perspective, a valuable resource has been poorly utilized and an energy and CO_2 reduction tool (BHEs) can be associated to a poor reputation. In fact, a life cycle impact assessment on shallow geothermal systems in Europe (Saner et al. 2010) found the resulting CO_2 savings were negative in many countries (up to -31%) as compared to conventional heating systems such as oil-fired boilers and gas furnaces. Thus, the BHE systems were producing more CO_2 than what would have been produced with the use of oil or gas. This essentially points to a failure of BHE systems to perform as expected. The problem here is not strictly related to the groundwater conditions in which the system is installed, but also the amount of energy used to run the heat pump, thus requiring coupled mechanical and hydrogeological approaches to solve the problem. Lack of urban or groundwater temperature data proximal to the BHE leads to less efficient BHEs, but these cases are not widely reported. The systems outlined in Florea et al. (2017) are an exception. Furthermore, studies of aquifer temperature at a city scale such as Mueller et al. (2018), Zhu et al. (2015), Garcia-Gil et al. (2014), and Ferguson and Woodbury (2007), clearly illustrate BHEs operating in such environments may be experiencing less efficient operations. Clearly, as noted by Vienken et al. (2015), Dehkordi and Schincariol (2014b), and Haehnlein et al. (2013), the approach to low temperature geothermal energy development must change. However, while awareness, investigative techniques, and numerical models are all encompassing in the research environment, the geothermal industry has generally not advanced beyond applying general analytical models, limited TRTs, and employing methods that minimize installation costs. This is largely because either a lack of regulation, or reliance on voluntary or non-enforceable regulations. Perhaps, due to the focus on minimizing installation costs for the HVAC industry, hydrogeologists will see their expertise utilized in one of our more traditional fields – groundwater remediation. Horst et al. (2018) look at how low-temperature thermal remediation utilizing BHEs is gaining traction for the in-situ remediation of certain organic contaminants. Horst et al. (2018) describe how “a little heat goes a long way” delivering order-of-magnitude improvements in active biodegradation rates.

Conclusions

Clearly, while there is abundant published research, in both mechanical engineering and hydrogeology disciplines, which shows how complex shallow groundwater systems and non-uniform temperature conditions can impact BHE design, the low temperature geothermal industry has not embraced complete analyses beyond general analytical codes and largely assumed uniform ground conditions. Even a properly conducted TRT only provides the effective ground thermal conductivity at the time of the test. Hydraulic gradients can change in magnitude and direction seasonally, and with periodic infiltration events. As BHEs only interact thermally via conduction with flowing groundwater, adverse system performance requires more time to become apparent as the system inefficiencies often simply reduce heat pump COP or EER and increase electricity consumption. Similarly, interactions between BHE fields and infrastructure in urban areas are slow to manifest and are often unrealized due to a lack of subsurface temperature data. Thus, clear regulations supporting sustainable thermal designs and performance in line with urban planning, currently either voluntary, unenforceable, or non-existent, are needed. As discussed in Dehkordi and Schincariol (2014b) in their global review of BHE regulations, even well laid out regulations that include hydrogeological factors, such as CSA (2007) that have now evolved in ANSI/CSA (2016), are voluntary, and are commonly unapplied in industry. Clearly, this gap between academic research and industry application needs to be addressed. How to address it is a much more difficult question with unsolved challenges for the new generation of practitioners to tackle. A multidisciplinary training based on both mechanical engineering and hydrogeological fundamental knowledge can be a key. However, this can be limited by the different heating-cooling options available to industry and competing with ground coupled heat pumps. The utilization of BHE systems can grow but will likely cover a small segment of the North American HVAC market, as designing and installing thermally efficient systems can be costly. Perhaps the role of hydrogeologists for BHE research and development can be naturally found in the soil and groundwater chemical remediation industry, one that we are familiar with. In that sense, hydrogeologists can make sure BHE systems complies with environmental regulations to protect groundwater resources and may be able, at the same time, to help improve system efficiency and profitably considering advective heat transport due to groundwater flow affecting BHE operation. We are still far from reaching that goal but greater interaction between mechanical engineers and hydrogeologists is needed to move into this direction.

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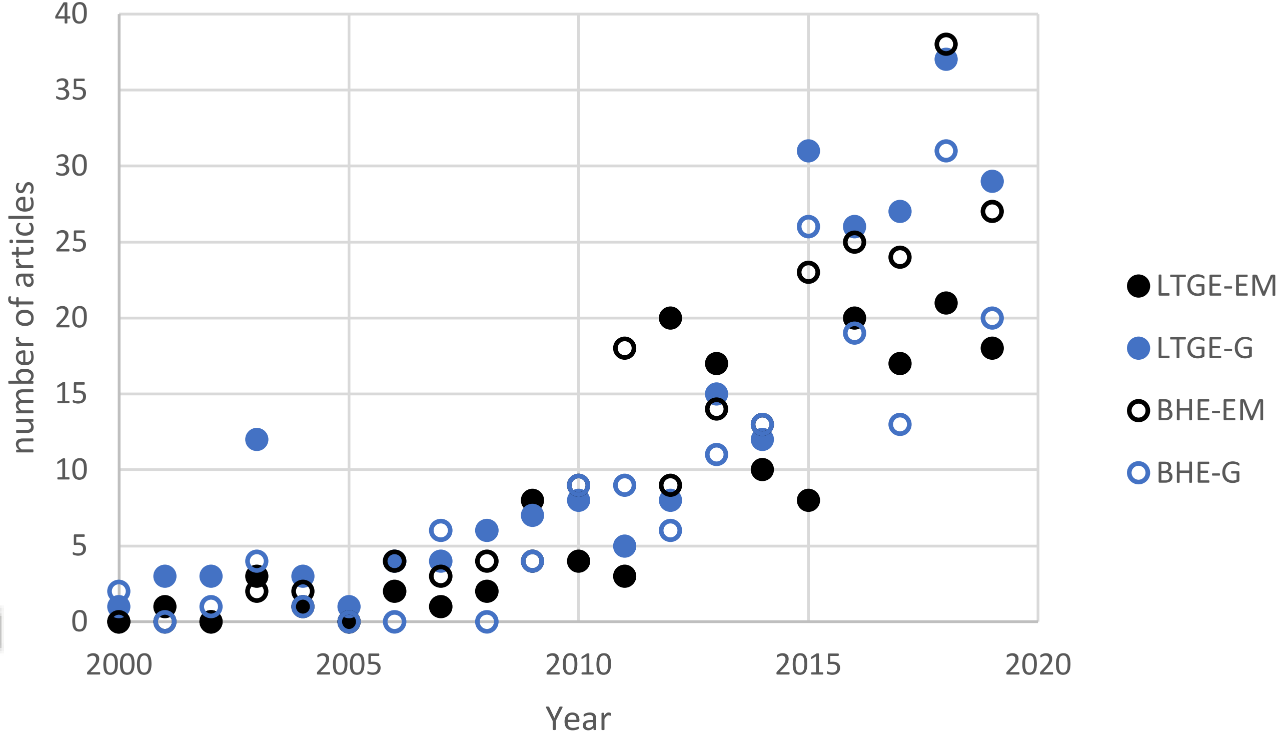
List of Figures

Figure 1. Number of published articles with search terms ‘low temperature geothermal energy’ (LTGE) and ‘borehole heat exchangers’ (BHE), under the fields of ‘Engineering Mechanical’ (EM) and ‘Geosciences’ (G), using *Web of Science*® search engine. Search range limited to years 2000 to 2020.

Figure 2. Graphic illustrating the different inputs for a typical HVAC type BHE design code, a hydrogeological code, and the coupling approach. COP = Coefficient of Performance.


40
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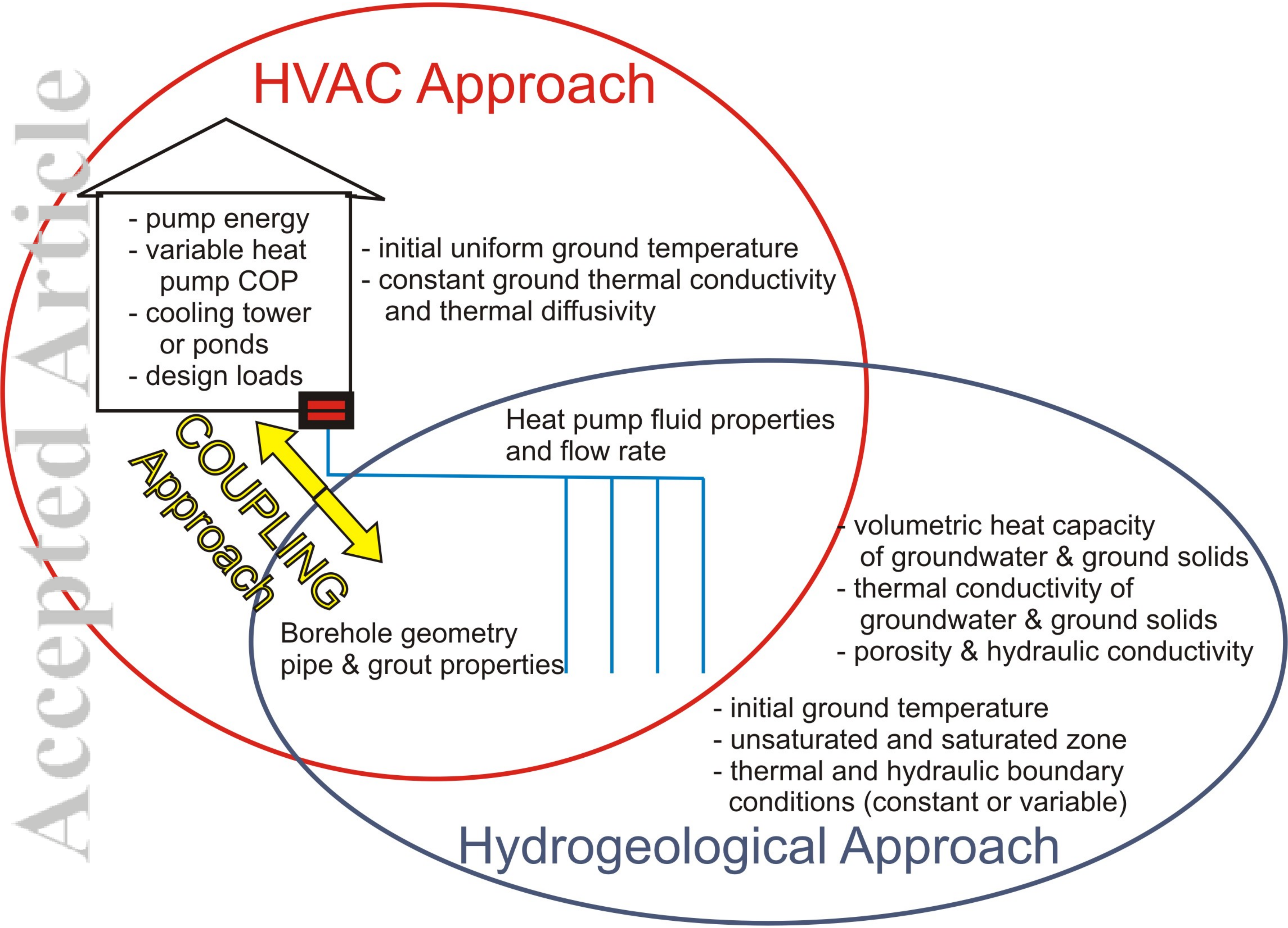
HVAC Approach
- pump energy
- variable heat pump COP
- cooling tower or ponds
- design loads
- initial uniform ground temperature
- constant ground thermal conductivity and thermal diffusivity
COUPLING Approach
Heat pump fluid properties and flow rate
Borehole geometry pipe & grout properties
- volumetric heat capacity of groundwater & ground solids
- thermal conductivity of groundwater & ground solids
- porosity & hydraulic conductivity
- initial ground temperature
- unsaturated and saturated zone
- thermal and hydraulic boundary conditions (constant or variable)
Hydrogeological Approach