ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

ESTIMATION OF FORMATION TEMPERATURES FROM RETURN LINE MUD TEMPERATURES FOR SEVERAL GEOTHERMAL FIELDS

M.Sc. THESIS

Oğuz Berk EVCİMEN

Department of Petroleum and Natural Gas Engineering

Petroleum and Natural Gas Engineering Programme

JULY 2019

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

ESTIMATION OF FORMATION TEMPERATURES FROM RETURN LINE MUD TEMPERATURES FOR SEVERAL GEOTHERMAL FIELDS

M.Sc. THESIS

Oğuz Berk EVCİMEN
(505151522)

Department of Petroleum and Natural Gas Engineering

Petroleum and Natural Gas Engineering Programme

Thesis Advisor: Asst. Prof. Dr. Mustafa Hakan ÖZYURTKAN

JULY 2019

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BİR TAKIM JEOTERMAL SAHALARIN GERİ DÖNÜŞ HATTINDAKİ ÇAMUR SICAKLIKLARINDAN FORMASYON SICAKLIĞININ TAHMİN EDİLMESİ

YÜKSEK LİSANS TEZİ

Oğuz Berk EVCİMEN
(505151522)

Petrol ve Doğal Gaz Mühendisliği Anabilim Dalı

Petrol ve Doğal Gaz Mühendisliği Programı

Tez Danışmanı: Dr. Öğr. Üyesi Mustafa Hakan ÖZYURTKAN

TEMMUZ 2019

Oguz Berk EVCIMEN, a M.Sc. student of ITU Graduate School of Petroleum Engineering student ID 505151522, successfully defended the thesis entitled "ESTIMATION OF FORMATION TEMPERATURES FROM RETURN LINE MUD TEMPERATURES FOR SEVERAL GEOTHERMAL FIELDS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor: **Asst. Prof. Dr. Mustafa Hakan ÖZYURTKAN** ....
                        Istanbul Technical University

Jury Members: **Asst. Prof. Dr. Yıldıray PALABIYIK**   ....
                     Istanbul Technical University

                     Asst. Prof. Dr. Ali ETTEHADI   ....
                     Izmir Katip Celebi University

Date of Submission : 03 May 2019
Date of Defense   : 18 July 2019

To my family,

FOREWORD

I would like to thank my thesis advisor Asst. Prof. Dr. Mustafa Hakan ÖZYURTKAN for his support and guidance on my thesis.

Finally, I would like to thank my family and my friends for their support during this study.

TABLE OF CONTENTS

NOMENCLATURE

α	: Thermal Diffusivity, $\frac{sq\,ft}{hr}$
c_c	: Specific heat capacity of clay, $\frac{BTU}{°F.lb}$
c_f	: Specific heat capacity of formation, $\frac{BTU}{°F.lb}$
c_p	: Specific heat capacity of mud, $\frac{BTU}{°F.lb}$
D_e	: Equivalent diameter, ft
$Dpipe_{,ID}$	: Inner diameter of drill pipe, ft
$Dpipe_{,OD}$	: Outer diameter of drill pipe, ft
D_{wb}	: Wellbore diameter, ft
$f(T_D)$	: Dimensionless temperature function, unitless
G	: Geothermal gradient, °F/ft
H	: Well Depth, ft
$h_{annulus}$	: Heat transfer coefficient across annulus, $\frac{BTU}{°F.ft^2.hr}$
h_{pipe}	: Heat transfer coefficient across drill string, $\frac{BTU}{°F.ft^2.hr}$
k_{cement}	: Thermal conductivity of cement, $\frac{BTU}{°F.ft.hr}$
k_f	: Thermal conductivity of formation, $\frac{BTU}{°F.ft.hr}$
k_{mud}	: Thermal conductivity of mud, $\frac{BTU}{°F.ft.hr}$
k_{steel}	: Thermal conductivity of steel, $\frac{BTU}{°F.ft.hr}$
m	: Mass flow rate, lb/hr
μ_p	: Plastic viscosity of mud, cp
$N_{Prandtl}$	: Prandtl number
$N_{Reynold,annulus}$	: Reynold number across annulus
$N_{Reynold,pipe}$	: Reynold number across pipe
Q	: Volumetric flow rate, gph
Q_{af}	: Heat transfer between annulus and formation, BTU/hr
Q_{ap}	: Heat transfer between annulus and drill string, BTU/hr
Q_{ax}	: Heat transfer across annulus at length of x, BTU/hr
ρ	: Mud density, lb/gal
ρ_f	: Density of formation, lb/gal
r_{ci}	: Inner radius of casing, ft
r_{co}	: Outer radius of casing, ft
r_p	: Inner radius of drill pipe, ft
r_w	: Wellbore radius, ft
T_a	: Annulus temperature, °F
T_D	: Dimensionless temperature, unitless
t_{drill}	: Drilling time, hr
T_f	: Formation temperature, °F

T_p **:** Drill pipe temperature, °F

T_{pi} **:** Inlet mud temperature, °F

T_{wb} **:** Wellbore temperature, °F

T_s **:** Surface temperature, °F

U_a **:** Overall heat transfer coefficient across annulus, $\frac{BTU}{°F.ft^2.hr}$

U_p **:** Overall heat transfer coefficient across drill string, $\frac{BTU}{°F.ft^2.hr}$

x **:** Bit depth, ft

V **:** Mean fluid velocity, ft/hr

LIST OF TABLES

LIST OF FIGURES

ESTIMATION OF FORMATION TEMPERATURES FROM RETURN LINE MUD TEMPERATURES FOR SEVERAL GEOTHERMAL FIELDS

SUMMARY

Formation temperature is a key information for geothermal fields. It determines producibility and sustainability of a well. Energy that is produced from well depends on formation temperature. Greater values of formation temperature mean more energy. Formation temperature is affected by underground hot water resources. Steam is generally used to produce electricity from geothermal wells. The power depends on energy of steam which can be tracked by observing higher temperature. There are many geothermal fields and operated to produce electricity.

The estimation and detection of the formation temperature is crucial for geothermal applications. Downhole temperature tools which can detect exact temperature values have been using for many years. Also, there are many models to estimate relationship between wellbore and formation temperatures. These models are conducted analytically by heat transfer mechanisms. Heat transfer is occurred in underground layers where formation and wellbore are connected with each other. The main aim is to conduct relationship between these sections. That relationship is based on heat balance. Heat balance equation is the main and simple form of this relationship. After conducting of heat balance equations between those sections, solutions are obtained analytically using differential equations. To use these equations, some reasonable assumptions may be needed in case of any lack of data.

In this study, formation temperature is estimated from drilling wells. Formation temperature models are used by adding drilling, wellbore and formation parameters. Models are conducted by heat transfer mechanisms which are heat convection and conduction systems. Overall heat balance equation is computed by combining heat transfer between formation-annulus and annulus-drill pipe.

Those equations are solved under steady state linear heat transfer conditions. Transient heat transfer happens in the formation surrounding the borehole. To solve equations analytical approaches are used. The approaches which are annulus-formation and annulus-drill pipe are different. According to those solutions, formation temperatures can be obtained and compared.

The most important reason of estimation of formation temperatures is to obtain geothermal gradients of that fields. Then, bottom hole temperatures need to be detected. To obtain those temperatures, wells can be drilled. Calculations are made using analytical approaches and return line mud temperatures during drilling. For those calculations, this study should be investigated in two sections which are before and after the cooling tower. While cooling tower is in progress, flowline temperatures decrease and decaying of chemicals can be prevented which are additive for drilling fluid.

The other key factor in estimating the formation temperatures is heat transfer. Heat transfer is occurred by a fluid or by a material. During drilling, heat transfer is occurred through a drilling fluid. In dynamic conditions like fluid circulation, heat transfer exists. Heat transfers are evaluated separately for each field. Heat transfer is affected by drilling parameters, mud properties, circulation parameters, drill string properties and lithology properties. Those parameters determine flow regimes and related calculations.

Potential of each fields can be detected by estimation of formation temperatures. According to those potentials, high temperature fields and low temperature fields can be evaluated to produce electricity or traditional investments. To produce electricity, exploration of the field is more important. To explore those fields, firstly drilling is needed, then temperatures of the wells can be detected. According to those temperatures, energy potential of the reserve can be determined. Then, production can be started.

There are many fields experiencing high temperature zones. The major reason of these high temperatures is lithology. Drilling of the metamorphic or igneous rocks is important step to reach energy. To produce energy, companies are effective in those fields and they get valid result from those fields.

If potential of those fields is considered and drilling activities are increased and theoretical can be run accurately, then, these may lead to decide to provide investment to install power plants.

In this study, mud temperatures are also calculated regarding drill string and annular depths. Calculation of those temperatures provides information about temperature of zone of interest. If high temperature zone is encountered, drilling fluid can be treated by adding chemicals. When the homogeneity is considered in drill string, temperature variations of the annulus give an idea about formations. By using temperature difference between bottom hole and surface, heat losses can be estimated. Also, those temperature values at drill string and annulus can be important parameter for cementing operations at the beginning of the following sections.

Estimation of formation temperatures provides information about main production zone temperature. So, the necessary predictions can be made like qualification of the well in terms of temperature. In geothermal fields, reserve zones can be metamorphic or igneous rocks. Hot zones are reached by drilling. For this study, there are four vertical wells. Sudden increasing of mud temperatures and lithology of the metamorphic or igneous rocks that is obtained from cuttings can show reserve zone. In this study, lithology is the marble which is the metamorphic rock for production zone. Also, geothermal gradient can be obtained from flowline temperatures that are indication of sudden temperature increasing. Flowline temperatures can be interpreted for four wells in this study. Formation temperatures can be evaluated by interpreting temperature differences between reserve zone and previous section. According to formation temperature values, the zones can be resource of geothermal energy.

BİR TAKIM JEOTERMAL SAHALARIN GERİ DÖNÜŞ HATTINDAKİ ÇAMUR SICAKLIKLARINDAN FORMASYON SICAKLIĞI TAHMİNİ

ÖZET

Jeotermal sahalar için formasyon sıcaklığı bir anahtar veridir. Kuyunun üretkenliğini ve sürdürülebilirliğini belirler. Bir kuyudan elde edilen enerji formasyon sıcaklığına bağlıdır. Yüksek sıcaklık değerleri daha fazla enerji demektir. Formasyon sıcaklığı yer altı sıcak su kaynaklarından etkilenir. Genellikle, buhar jeotermal kuyulardan elektrik enerjisi üretebilmek için kullanılır. Elde edilen güç yüksek sıcaklıklar gözlemlenerek izlenebilir olan buhar enerjisine bağlıdır. Elektrik üretmek ve işletmek için çok fazla jeotermal saha mevcuttur.

Jeotermal uygulamalar için formasyon sıcaklığının tahmin edilmesi ve belirlenmesi önemlidir. Net sıcaklık değerlerini belirleyen yeraltı sıcaklık ekipmanları yıllardır kullanılmaktadır. Ayrıca, kuyu ve formasyon sıcaklıkları arasındaki ilişkiyi tahmin etmek için bazı modeller vardır. Bu modeller ısı transfer mekanizmaları vasıtasıyla analitik olarak oluşturulurlar. Isı transferi formasyon ve kuyunun birbiriyle bağlantılı olduğu yerde yeraltı tabakalarında meydana gelir. O yerlerde ilişkiyi kurabilmek ana amaçtır. Aralarındaki ilişki ısı dengesine dayanır. Isı dengesi denklemi bu bağlantının ana ve basit formudur. O bölgelerde gereken ısı dengesi denklemlerini kurduktan sonra, diferansiyel denklemler kullanılarak analitik olarak sonuçlar elde edilir. Bu denklemleri kullanmak için, herhangi bir veri eksikliği durumunda mantıklı varsayımlarda bulunulabilir.

Bu çalışmada kuyu sondajlarından formasyon sıcaklığı tahmin edilmiştir. Formasyon sıcaklık modelleri sondaj, kuyu ve formasyon parametreleri eklenerek kullanılmıştır. Modeller ısı iletimi ve taşınımı olan ısı transfer mekanizmaları ile oluşturulmuştur. Formasyon-anülüs ve anülüs-sondaj dizisi arasındaki ısı transferleri birleştirilerek ortalama ısı dengesi denklemi kurulmuştur.

Bu denklemler düzenli doğrusal ısı transferi durumu altında çözümlenmiştir. Kararlı ısı transferi etrafı kuyu ile çevrilmiş formasyonlarda meydana gelir. Denklemleri çözmek için analitik yaklaşımlar kullanılmıştır. Anülüs-formasyon ve anülüs-sondaj dizisi arasındaki çözümlemeler için yaklaşımlar farklıdır. Bu çözümlemelere göre formasyon sıcaklıkları elde edilebilir ve karşılaştırılabilirler.

Formasyon sıcaklıklarının belirlenmesindeki en önemli araç bölgelerin jeotermal gradyant dağılımlarını belirleyip, o bölgelerin sahip olabileceği yer altı sıcaklıklarının belirlenmesi gerekmektedir. Bu sıcaklıkları elde edebilmek için yapılacak olan aktivite sondaj operasyonlarıdır. Sondaj operasyonları sırasında, çamurun dönüş hattındaki sıcaklıklarından faydalanarak analitik yaklaşımlarda bulunarak hesaplamalar yapılır. Bu hesaplamalar esnasında soğutma kulesinin devreye alınma öncesi ve devreye alındıktan sonrası diye iki kısımda incelenmesi doğru çalışmanın yapılmasına olanak sağlayacaktır. Soğutma kulelerinin devreye girmesiyle çıkan çamur sıcaklığı düşmekte olup, çamurun içinde bulunan

kimyasalların bozulmasının önüne geçilerek doğru sondaj çamurunun kullanılması mümkün olacaktır.

Formasyon sıcaklıklarının tahminindeki bir diğer temel madde de ısının taşınım olayıdır. Isının taşınması, bir akışkan veya madde aracılığı ile gerçekleşir. Sondaj operasyonları esnasında bu taşınmayı gerçekleştiren ana element sondaj çamurudur. Sondaj çamurunun sirkülasyon sırasındaki dinamik hareketi vesilesiyle ısı taşınımı ortaya çıkar. Bu taşınım da her bölge için farklı değerlendirilmiştir. Sondaj parametreleri, çamurun özellikleri, sirkülasyon parametreleri, sondaj dizisinin özellikleri ve litoloji bilgileri ısı taşınımı olayını etkilemektedir. Bu parametreler sonucunda akış rejimleri oluşmakta bu akış rejimlerine göre hesaplamalar yapılmaktadır.

Her bölgenin sahip olabileceği potansiyel formasyon sıcaklıklarının belirlenmesiyle açığa çıkarılır. Bu potansiyellere göre yüksek sıcaklığa sahip formasyonlar elektrik enerjisi üretmek için; daha düşük sıcaklığa sahip olan formasyonlar ise geleneksel yatırımlar adına değerlendirilebilir. Enerji üretebilmek adına yüksek sıcaklığa sahip sahaların keşfi daha fazla önem arz etmektedir. Bu keşiflerin yapılabilmesi için öncelikle sondaj yapılmalı ardından kuyuların sıcaklıkları tespit edilmelidir. Bu sıcaklıklara göre enerji rezerv potansiyeli belirlenerek gerekli üretim sağlanır.

Yüksek sıcaklıklarla karşılaşılan bazı sahalar bulunmaktadır. Bu bölgelerin bu denli yüksek sıcaklıklara sahip olmasının ana sebeplerinden biri yer altı jeolojisidir. Metamorfik veya volkanik kayaçların hedeflenen metrajlarda sondajının yapılması enerjiye ulaşmak adına atılan en önemli adımlardan birisidir. Şirketlerin birçok sondaj faaliyetleri bu sahalara yoğunlaşmış ve elektrik enerjisi üretebilmek adına kuyulardan olumlu sonuçlar alınmıştır.

Bu denli yüksek potansiyel göz önüne alınırsa sondaj faaliyetlerinin arttırılıp ve bu bölgeler için yapılacak olan teorik çalışmalar doğru bir şekilde uygulanırsa, bunlar belki de yatırım sağlanması ve santrallerin kurulması kararına vesile olacaktır.

Bu çalışmada ayrıca belirlenen derinlikteki anülüs ve sondaj dizisi içindeki çamur sıcaklıkları hesaplanmıştır. İstenilen derinlikteki anülüs veya sondaj dizisi içindeki çamur sıcaklıklarının hesaplanması o katmanın sıcaklığı ile ilgili bilgi vermesini sağlayacaktır. Eğer katmanda yüksek sıcaklık ile karşılaşılırsa ona göre çamura kimyasal takviyesi ile gerekli müdaheleler de bulunulabilir. Dizi içerisinin homojen bir yapıya sahip olacağı düşünülürse anülüsteki sıcaklık değişimleri formasyon ile ilgili daha net bilgiler verecektir. Belirlenen derinlikteki ve yüzeydeki çamur sıcaklık farkının kullanılması ile ısı kayıplarının da belirlenmesi kolaylaşacaktır. Ayrıca katmandaki anülüs ve dizi içerisi sıcaklık bilgisi, bir sonraki kısmın başlangıcında çimento operasyonu için önemli bir parametre olacaktır.

Formasyon sıcaklıklarının belirlenmesi, asıl üretim kaynağı olan rezervuar zonunun sıcaklığı hakkında da bilgi verecek olup, kuyuların sıcaklık açısından yeterliliğine dair gerekli tahminlerin yürütülmesini sağlayacaktır. Jeotermal kaynaklarda rezervuar zonu metamorfik veya volkanik kayaçlardan oluştuğu için, sıcak su kaynağının varlığının bulunması sondaj faaliyetleri kapsamında belirlenmektedir. Bu çalışma için dört tane dik kuyu vardır. Ani çamur sıcaklığındaki artışlar, çamurun taşıdığı kesintilerdeki litolojilerin metamorfik veya volkanik kayaç yapısına sahip olması gibi bilgiler sayesinde rezervuar zonu belirlenip hedef noktadaki üretim kaynağına ulaşılır. Bu çalışmada üretim zonu metamorfik bir kayaç olan mermerdir. Ani sıcaklık artışlarının olduğu bölgelerin çamur geri dönüş hattındaki sıcaklıklarından jeotermal gradyant hakkında bilgi sahibi olunur. Bu çalışmada geri

akış hattındaki sıcaklıklar yorumlanmıştır. Sıcak rezervdeki sıcaklıklar ve bir önceki kısım olan normal jeotermal gradyanta göre artışların gerçekleştiği katmanlardaki sıcaklık farkları yorumlanarak formasyon sıcaklıkları ile ilgili değerlendirmeler yapılır. Bu formasyon sıcaklıkları değerlendirmelerine göre, zonlar jeotermal enerji kaynağı olabilirler.

1. INTRODUCTION

Geothermal energy is the heat transfer to the surface by means of hot water and steam under pressure, which can contain more dissolved minerals, various salts and gases than the normal underground waters. Geothermal energy is generally obtained from surface water or specially drilled wells where weak zones formed by cracks and fractures.

The source of geothermal energy can be seen as water, steam, hot rocks and magma in the layers which are close to the earth. Fluid is overheated by the heat source that contains more molten minerals, various salts and gases than normal ground and surface waters.

Geothermal drilling techniques are basically the same as oil and natural gas drilling techniques. However, as a result of the experience, some different applications have been developed for geothermal drilling. Geothermal drillings can be classified as gradient, exploration, production, development, re-injection and observation wells.

Geothermal drillings are used in geology, geochemistry, hydro geochemistry, geophysical studies and evaluations. The interpretations and the conceptual model are tested for reservoir exploration and production purposes. The steps to be followed during drilling are grouped under five main headings. Those are well program, drilling, casing, cementing, well tests.

According to the data obtained from geological, geochemical, hydrogeological and geophysical surveys; well depth, possible lithological log, possible casing plan are prepared. The lithological log contains geothermal parameters and geological zones which are zones that may form cap rock, reservoir zones, temperature levels that may be encountered, zones likely to be taken from coring, zones that may interfere with cold groundwater, possible chemistry of the fluid to be encountered in the well. Well diameter and depth, casing type, diameter and running depth, mud type and quantities of additional materials (bentonite, barite, drilling foam, etc.), zones to be cemented and its program, cement type and quantity are determined by the

responsible person in charge of the drilling process. Drilling techniques can be applied according to collapse, fluid loss and swelling, zones that can cause sudden kick (fluid, gas, steam) situations (Aytekin, 2016).

During the well drilling process, the first observations are measurement of inlet and outlet temperatures of mud at each meter for geothermal purposes, investigation of rock fragments coming with mud at each meter, changes in mud salinity, color change in mud, viscosity change in mud, gas, bubble in the mud, determining the core drilling, providing well logging at the required level, blow-out risk monitoring (Aytekin, 2016).

Drilling mud is a fluid used for drilling wells in oil, natural gas or geothermal wells. The main functions of drilling fluid are cooling the bit in the well during drilling, transmitting hydraulic energy to this bit, reducing the weight of the drill string with the buoyancy force, cleaning the fragments that occur as the drilling progresses in the well and ensuring that these fragments in the well are suspended during the drilling (Bourgeyne et al, 1986).

The aim is to keep the well clean and to keep the drilling smoothly by removing the rock pieces and cuttings. The faster the cuttings are transported from the bottom hole, the faster the drilling progresses. In order for the parts to be transported upwards, the drop rates in the mud must be less than the rise rate of the mud. Fragments in the mud not only cause the metal parts to wear out during circulation, but also play a negative role in terms of mud flow properties, mud cake formation and temperature resistance. The heat generated during operation of the bit at the bottom of the well is cooled by means of circulating mud. In addition, the mud plays a lubricating role by covering the surfaces of the pipes, the wall of the well, the surface of casings, the wearing parts of the pumps and the drill bits in a thin film. It is possible to reduce friction losses by incorporating certain special lubricants into the mud. With the help of some other additives to be added to the drilling mud; prolongs the life of the bit, prevents stucking, reduces the wear on the pipes and protects against corrosion. Especially oil and oil-based muds have high lubrication properties. During drilling, the pressure of drilled formations in the well should be higher than the pressure coming from the formation in order to prevent the well from collapsing and collapsing into the well hole. In particular, the mud entering the sand and gravel layers solidifies and attaches them to each other. Due to hydrostatic pressure, drilling

mud adheres to the well wall to form a mud cake. This mud cake provides impermeability. If the mud is of good quality, the thickness of the cake will be low as the filtration water will be low. Thus, the well will not narrow and the drilling sequence will work more easily. If the water of the mud will escape to a large extent, the cake will thicken and the well will narrow. If the hydrostatic pressure in the wells is less than the formation pressure, there is a danger that oil, gas or water in the formations will flow into the well and rise upwards. In this respect, the density of the mud should be increased to a value that prevents flushing. By increasing the density of the mud there is a reduction in the rate of penetration. In some cases, mud escaping from weak formations may occur. The mud must be well pumped along with many features. The mud carrying capacity increases viscosity. In order to ensure good mud circulation, the pumps must continuously measure the viscosity, gel strength and solids content of the mud and keep it under control. Low-concentration salt solutions cause corrosion to a great extent in pipes and casings. During the passage of salty formations, chemicals are added to prevent the corrosion caused by the salt mixed with the mud (Korkmaz, 2014).

One of the most important elements of geothermal energy systems is geothermal fluid. Heat in the ground heats fluids (liquids and gases) trapped or circulated in rocks by different conduction paths (convective, conductive, etc.). All of these heated liquids or gases are called geothermal fluids. These fluids that include heat are transferred.

Heat transfer is the study of the energy transfer between two or more objects whose temperatures are different by conduction, convection or radiation (or combinations of these paths with each other). Mathematical modeling of this transfer is the main subject of heat transfer course. Thermodynamics is related to fluid mechanics and materials.

Convective heat transfer is mainly caused by the mass movement of molecules. Fluid in motion between two different temperature surfaces provides heat transfer during this movement.

In radiation heat transfer, no environment is required for heat transfer. It is possible to say that as long as there is a difference in temperature between the exposed surfaces, heat transfer by radiation is possible.

The issue of heat transfer is finding application in all branches of engineering today. Heat transfer, heating, cooling, air conditioning, ventilation in other internal combustion engines, steam production, the design of heat exchangers and many other branches of engineering are widely used. Heat transfer theory can be explored to a large extent with advanced physics and advanced mathematics applications, and can provide a mathematical solution to most problems only by simplifying and making some assumptions.

Heat conduction is the process of heat transfer between the zones in a medium or between different mediums in direct physical contact, resulting from their direct contact without noticeable displacement of atoms and molecules. According to the thermodynamics second law, heat flows from a high temperature zone to a low temperature zone. According to kinetic theory, the temperature of a substance is proportional to the average kinetic energy of the molecules or atoms that make up that substance. Excess kinetic energy means more internal energy. Kinetic energy means more. More kinetic energy means more internal energy. If the average kinetic energy of the molecules in a region is more than the average kinetic energies of the molecules in the adjacent region due to the temperature difference, the energetic molecules transmit this energy to the neighboring molecules (Yıldız, 2016).

Convection is the process of energy transport by fluid motion. If the medium is a liquid or gas, heat energy will be transferred from one region to another due to the temperature difference by fluid movement. Convection is the most important issue of heat transfer. Since fluids in heat exchangers are separated from solids (surfaces), convection is the most important heat transfer mechanism in energy transport between a surface and fluid. The air in the cooler is the main example of the result of the convection current. The factors affecting the velocity of convection are the surface area, the coefficient of heat transfer and the temperature difference between the substances to be transferred. The heat transfer coefficient of these factors is the quantity specification. The higher the heat transfer coefficient of a material, the better the heat convection. The surface area is considered as the application area between convection and heat transfer materials. The higher the surface area, the more efficiency is achieved. The higher the temperature difference between the substances, the faster the heat transfer is occurred (Yıldız, 2016).

Temperature log is the most important well log in geothermal exploration and development. For the high temperature wells which can range from 150 °C and 380 °C. The main aim of temperature logging is to determine formation temperatures. After the drilling, there is heating and recovery periods. During this period, temperature logs can estimate the formation temperature.

Kuster temperature gauges have been used. This tool is used for multiple tasks like temperature and pressure measurement. The gauge is run into the well on a slickline. Temperature is recorded by a pen needle on a carbon coated brass foil which is inside clock driven recorder. Firstly, dummy run can be run to see open hole section. If there is no problem in the wellbore, then temperature log tool can be run. The gauge is valid with accuracy of +/-2 °C (Steingrimsson, 2013).

According to Steingrimsson (2013), "The tool has been developed for years. The last product is combined with pressure gauge and called as PT tool. The tool is run into the well with the speed of 30 m/min. Data is recorded for every second. For this tool, the accuracy of the measurements is +/- 0.5 °C".

Measurement while drilling is a tool which is developed to record drilling related measurements at the down hole and transmit to the surface. It is connected to bottom hole assembly.

MWD can record temperature measurement. It transmitted the measurements to the surface through mud circulation system as positive or negative pulses. Those pulses can be shown digital acoustic signals. Signals are detected with pressure transducers in the standpipe. For records, drilling process is stopped. Especially, measurements are obtained in connection times. Electrical energy can be provided for the system by battery pack. Measurements are recorded and stored in the microprocessors which are located in battery pack. At the wellsite, data is shown on monitors located in the logging unit (Crain, 2015).

MWD also provides information about rate of penetration, rotational speed of the drill string, type and severity of the vibration, torque, weight on bit. The main aim is to determine well deviation and azimuth. Dog leg severity can be detected using inclination at each 100 feet. So, directional drilling and torque-drag analysis can be determined according to those parameters.

1.1 Problem Statement and Significance of Study

Transient heat transfer data has been limited in geothermal wells because of lack of analytical and computational models which aim to understand formation information especially about temperature while drilling has been occurring. In this study, formation temperature data is computed using heat balance equations and transient heat transfer for different wells.

Also, the other problems are logging and downhole temperature tools. They give the necessary information about temperatures. Actually, this means simplicity. Without any calculation, temperatures are obtained, but the problem is timing. To determine temperatures at certain depths with those tools, tripping is needed. So, this means losing time and extra costs. To measure exact and reliable temperature values, off set wells may be needed.

The main objective of this study is to develop formation temperature models from the information obtained from geothermal well drilling activities for four wells. They consist of four stage. Formation includes metamorphic rocks for final stage. Heat balance equations between drillpipe-annulus and annulus-formation are derived by heat convection and conduction models. The heat transfer equations are solved for finding formation temperatures at steady state heat transfer by using analytical approaches.

Transient heat transfer data provides many additional information especially about wellbore and formation temperature. To analyze transient heat transfer data, several methods have been used analytically. In this study, analytical approximation is developed. The significance of the study is determination of formation temperature data obtained from drilling operations. Also, drill pipe and annulus temperatures are considered for relationship with formation. This study also provides new observations and information about the formation temperature distributions for certain fields to have any idea for further possible drilling activities.

Finally, a study has not been conducted in geothermal fields previously. So, this study is very important at that region in terms of new studies for next times, evaluate the results comparing with other regions.

1.2 Background and Literature Review

Estimation of the formation temperatures can give an idea on the energy occupied by these formations. In geothermal well drilling, transient heat transfer data are usually used for estimation of formation temperature, drillpipe and annulus temperatures to lead assistance further drilling operations like cementing and mud selection. Transient heat transfer data are also used not only for the purpose of formation temperature estimation but also for the determination of drilling and wellbore parameters such as temperatures at drillpipe and annular section and drilling fluid properties that are related to temperature and designing cement. Developments in formation temperature modeling have increased the interest using transient heat transfer data.

In Hasan and Kabir (1991), Holmes and Swift (1970) studies, modeling transient heat transfer data is obtained by using formation characteristics and drilling parameters. In addition, drillstring specifications affects this models. To determine it, flow regimes have to be considered which are laminar, turbulent and transition.

Holmes and Swift (1970) presented an analytical solution assuming steady state linear heat transfer. Heat is ignored which is generated by drillbit. Their solution is based on the heat balance equation. Holmes and Swift (1970) also divided into two parts their solutions because the reaction is occurred between formation-annulus and annulus drillpipe. Temperatures can be estimated before logging operations. In their study, there is a well which has 15000ft depth. Also, the well is assumed wholly open hole and same bore size from the beginning of the drilling. They researched effects of changing pipe diameter, heat transfer coefficients and mud flow rates on the drill string and the annulus mud temperatures. After finishing the drilling of well, logging can be applied and results are compared. Results are compatible with each other. They showed that highest mud temperature is observed at annular section which is above bottomhole. According to their study, proper drilling fluid and cement programme can be prepared for further drilling operations referring to valid results of their study.

Hasan and Kabir (1991) presented an analytical solution assuming constant heat flux, cylindrical source well. Dimensionless time equation is computed. Drilling fluid is incompressible. Flow rate has a constant rate. Axial conduction is ignored in drilling

fluid compared with axial convection. This condition can be applied for vertical wells. Radial temperature gradients are ignored in drillpipe, annulus. At the outer boundary conditions, formation temperature does not change with radial distance. The physical properties of drilling fluid does not change with temperature. The formation is symmetric, so mathematical equations can be applied for two dimensional problems, but their study is presented for one dimensional heat transfer with initial and boundary conditions. Lithological properties which forms formation is also taken into account. Firstly, formation temperature is distributed as function of radial distance and time. Their study is based on production wells, but it may be applied for injection wells. The vertical well is considered. According to their study, formation temperatures can be predicted in the formation at all times using transient heat transfer model. The other studies are presented for earlier or larger times.

Aadnoy and Karstad (1997) investigated temperatures during drilling activities. They did this study for high temperature – high pressure wells because of unlucky event that happened in Norway. Underground blowout happened while drilling was going on. According to their study, high temperatures which are related to pressure variations affect the mud properties. Proper mud density, reservoir and borehole stability can be analyzed. Transient heat transfer model model is used in their study. Changings in mud volume and mud density can be caused by high temperature effects. Drill pipe acts counter heat exchanger. Because of this situation, inlet and outlet mud temperatures have different temperature values. Formation temperature has higher value than wellbore temperature. The reasons are conductivity of the formation and time exposure at the open hole section. In this study, equations are solved for all models which are static, forward and reverse circulations. Formation temperatures are observed with different parameter selections. Those are flow rates, times and depths. While flowline temperatures are increasing, the mud temperature of the active pit is also increasing, so inlet mud temperature increases. There also another reasons for increasing inlet mud temperatures which are heat capacity and heat losses of the active pit. In their study, bottomhole temperatures show linear increasing with depth. It also depends on mud flow, drill string rotary and drill bit energy during drilling. If the inlet mud temperature is constant during drilling, formation temperature can be equal bottomhole temperature. Circulation without drilling cools the bottomhole. The cooling depends on circulation time and the flow

rate. In their study, they used parameters of the Holmes and Swift's study. Finally, their study is valid for short times.

Raymond (1969) predicted mud and formation temperatures during circulation time. Modern techniques which are formed for tripping times are developed for circulation time. Dynamic conditions are provided circulating drilling fluid through wellbore and drillstring. There is a well in his study which has 20000ft depth. Oil based mud is used. Solutions depends on time, depth and temperature values. In pseudo steady state model, temperature of mud shows logaritmic decline. After some times, results are same with results of unsteady state model. Pseudo steady state model can be valid for temperature calculations for long circulating times. Unsteady state model can be used for earlier times. In tripping times, there is a free convection or conduction in the formation. There is no forced convection conduction. Because of that reason, heat conduction can be ignored for the fluid. So, calculations are made according to heat conduction in the formation. Radial diffusivity equation is used. In his study, mud type, flow rate and depth are investigated for effects on bottomhole temperatures. According to his study, the most effective parameter is flow rate that affects the bottomhole temperature. Oil based mud has greater values than water based mud in terms of differences between bottomhole and flowline temperature. There are some assumptions of his study. Those are negligible axial heat conduction, no radial gradient of the fluid, constant fluid properties and negligible heat generation of the fluid. Finally, higher mud temperatures can be observed mostly annulus. Temperatures change with time. In tripping, mud temperature is a function of the depth.

1.3   Structure of Thesis

Structure of thesis is stated by sections beginning from the section 2 as follows:

In Chapter 2, the derivation and properties related to the heat balance equation that provides partial derivatives of temperatures for annulus and drill pipe which contains heat conduction and convection models is given. Equation is derived by heat transfer functions. Then, assumptions are applied. There is a partial differential equation which is developed by Hasan et al. (1991). After applying all boundary conditions, heat balance equation is solved with provided well data records.

In Chapter 3, heat balance equation in the form of partial differential equations for a geothermal well is analytically solved by Holmes et al. (1970).

In Chapter 4, the heat flow regimes and related equations are explained for cased and cemented holes

In Chapter 5, evaluation of the study is presented for geothermal well drilling.

In Chapter 6, results of both methods in terms of formation, annulus and drill pipe temperatures are stated in conclusion part.

2. ANALYTICAL SOLUTIONS OF HEAT BALANCE EQUATION

In this section, general derivation of heat balance equations is provided for determination of formation temperature. To derive these equations, the following assumptions as also stated in Hasan et.al (1991) are made:

1. The drilling fluid is incompressible,

2. Flow rate during drilling is constant,

3. Axial heat conduction is negligible,

4. Radial temperature distribution is negligible,

5. Constant geothermal gradient exists,

6. The physical properties of drilling fluid and formation do not vary with temperature,

7. The formation is symmetric,

8. The energy of flow is negligible which is formed by viscous drilling fluid,

9. During drilling, the energy which is formed by rotary is negligible,

10. Transient heat transfer happens at the formation where surrounds the borehole,

11. The energy of drill bit is negligible.

To derive these equations, the following assumptions as also stated in Holmes et.al (1970) are:

1. Heat transfer is steady-state,

2. Heat generation by drill bit is negligible,

3. Constant geothermal gradient exists,

4. Radially heat transfer is occurred,

5. There is no remarkable longitudinal heat conduction.

2.1 Heat Balance Equation for Geothermal Wells

In this subsection, heat balance equations are derived for a well. There are two partial differential equations which are combined for solution after computing equations as seen in Figure. 2.1. (Holmes and Swift, 1970).
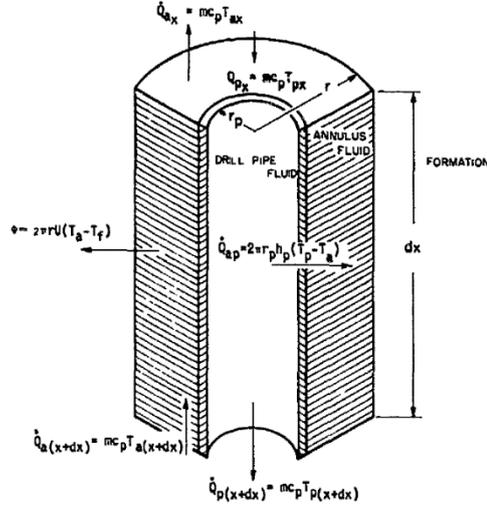
Figure 2.1: Differential derivation model (Holmes and Swift, 1970)

The heat accumulation through annulus is considered between at depth x and x + dx (Eq. 2.1).

$$Q_{ax} - Q_{a(x+dx)} = mc_p[T_{ax} - T_{a(x+dx)}] \tag{2.1}$$

where m is mass flow rate, c_p is specific heat capacity of drilling fluid and T_a is annulus temperature.

The heat transfer is occurred between formation and annulus (Eq. 2.2).

$$Q_{af} = 2\pi r_w U_a (T_a - T_f) dx \tag{2.2}$$

where r_w is wellbore radius, U_a is overall heat transfer coefficient across annulus and T_f is formation temperature.

Heat transfer is occurred across drill pipe (Eq. 2.3).

$$Q_{ap} = 2\pi r_p U_p (T_a - T_p) dx \tag{2.3}$$

where r_p is drillpipe radius, U_p is overall heat transfer coefficient across drill pipe and T_p is drill pipe temperature.

Heat transfer is occurred between formation and wellbore (Eq. 2.4).

$$Q_{af} = \frac{2\pi k_f}{T_D}(T_f - T_{wb})dx \tag{2.4}$$

where T_D is dimensionless temperature, k_f is thermal conductivity of formation and T_{wb} is wellbore temperature.

Assume that heat fluxes are equal at formation-wellbore interface,

$$Q_{af} = Q = \frac{2\pi k_f}{T_D}(T_f - T_{wb})dx = 2\pi r_w U_a(T_{wb} - T_a)dx \tag{2.5}$$

$$Q_{af} - Q = 2\pi r_w U_a(T_{wb} - T_a)dx - \frac{2\pi k_f}{T_D}(T_f - T_{wb})dx = 0 \tag{2.6}$$

$$r_w U_a T_D(T_{wb} - T_a) - k_f(T_f - T_{wb}) = 0 \tag{2.7}$$

$$T_{wb}(k_f + r_w U_a T_D) = k_f T_f + r_w U_a T_D T_a \tag{2.8}$$

Substituting eq. (2.8) into eq. (2.4)

$$Q_{af} = \frac{2\pi k_f}{T_D}(T_f \frac{-k_f T_f - r_w U_a T_D T_a}{k_f + r_w U_a T_D})dx \tag{2.9}$$

$$Q_{af} = \frac{2\pi k_f}{T_D}(\frac{k_f T_f + r_w U_a T_D T_f - k_f T_f - r_w U_a T_D T_a}{k_f + r_w U_a T_D})dx \tag{2.10}$$

$$Q_{af} = \frac{2\pi r_w U_a k_f}{k_f + r_w U_a T_D}(T_f - T_a) \tag{2.11}$$

Heat balance becomes,

$$mc_p[T_{a(x+dx)} - T_{ax}] = 2\pi r_p U_p(T_a - T_p)dx - \frac{2\pi r_w U_a k_f}{k_f + r_w U_a T_D}(T_f - T_a)dx \tag{2.12}$$

$$\frac{dT_a}{dx} = \frac{2\pi r_p U_p}{mc_p}(T_a - T_p) - \frac{2\pi r_w U_a k_f}{mc_p(k_f + r_w U_a T_D)}(T_f - T_a) \tag{2.13}$$

When these equations are combined, they yield (Eq. 2.14)

$$mc_p \frac{dT_a}{dx} + 2\pi r_p U_p(T_a - T_p) = 2\pi r_w U_a(T_f - T_a) \tag{2.14}$$

Similar solution is developed for drill string (Eq. 2.5).

$$mc_p \frac{dT_p}{dx} = 2\pi r_p U_p(T_a - T_p) \tag{2.15}$$

Defining $\frac{2\pi r_p U_p}{mc_p} = A, \frac{2\pi r_w U_a k_f}{mc_p(k_f + r_w U_a T_D)} = B$ for Hasan and Kabir method

Also defining, $\frac{mc_p}{2\pi r_p U_p} = A$, $\frac{r_w U_a}{r_p U_p} = B$ for Holmes and Swift method

$$\frac{dT_a}{dx} = A(T_a - T_p) - B(T_f - T_a) \tag{2.16}$$

Annulus temperature can be written as:

$$T_a = \frac{1}{A}\frac{dT_p}{dx} + T_p \tag{2.17}$$

$$\frac{d}{dx}\left(\frac{1}{A}\frac{dT_p}{dx} + T_p\right) = A\left[\left(\frac{1}{A}\frac{dT_p}{dx} + T_p\right) - T_p\right] - B[T_f - \left(\frac{1}{A}\frac{dT_p}{dx} + T_p\right)] \tag{2.18}$$

$$\frac{1}{A}\frac{d^2 T_p}{dx^2} + \frac{dT_p}{dx} = \frac{dT_p}{dx} + AT_p - AT_p - BT_f + \frac{B}{A}\frac{dT_p}{dx} + BT_p \tag{2.19}$$

$$\frac{1}{A}\frac{d^2 T_p}{dx^2} = \frac{B}{A}\frac{dT_p}{dx} + BT_p - BT_f \tag{2.20}$$

$$\frac{d^2 T_p}{dx^2} - B\frac{dT_p}{dx} - ABT_p = -ABT_f = f(x) \tag{2.21}$$

Partial solution of Eq. 2.21 is,

$$T_p = ax + b \tag{2.22}$$

Substituting eq. 2.22 into 2.21 is,

$$\frac{d^2(ax+b)}{dx^2} - B\frac{d(ax+b)}{dx} - AB(ax+b) = -ABT_f \tag{2.23}$$

$$-Ba - AB(ax+b) = -AB(T_f) \tag{2.24}$$

$$\frac{a}{A} + ax + b = T_f \tag{2.25}$$

where $T_f = T_s + Gx$ $\quad T_s$ is surface temperature and G is geothermal gradient

$$(a - G)x + \frac{a}{A} + b - T_s = 0 \tag{2.26}$$

Coefficients and constants are equal to zero. So, $a = G$ and $b = T_s - \frac{G}{A}$

$$T_p = Gx + T_s - \frac{G}{A} \tag{2.27}$$

Homogenous part of the eq. (2.21) is,

$$\frac{d^2 T_p}{dx^2} - B\frac{dT_p}{dx} - ABT_p = 0 \tag{2.28}$$

Polynomial equation of eq. (2.28) is,

$$C^2 - BC - AB = 0 \tag{2.29}$$

14

The roots are,

$$C_1 = \frac{B + \sqrt{B^2 + 4AB}}{2} \tag{2.30}$$

$$C_2 = \frac{B - \sqrt{B^2 + 4AB}}{2} \tag{2.31}$$

Then the solution is,

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} \tag{2.32}$$

Finally, drill pipe temperature is obtained by substituting eq. (2.27), (2.32) and (2.23).

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - \frac{G}{A} \tag{2.33}$$

To calculate annulus temperature, Eq. (2.33) is substituted

$$T_a = \frac{1}{A}\frac{d}{dx}\left(K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - \frac{G}{A}\right) + (K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - \frac{G}{A}) \tag{2.34}$$

$$T_a = \frac{1}{A}(C_1 K_1 e^{C_1 x} + C_2 K_2 e^{C_2 x} + G) + K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - \frac{G}{A} \tag{2.35}$$

$$T_a = \left(1 + \frac{C_1}{A}\right) K_1 e^{C_1 x} + \left(1 + \frac{C_2}{A}\right) K_2 e^{C_2 x} + Gx + T_s \tag{2.36}$$

To calculate constants K_1 and K_2, boundary conditions are used. At the surface, $x = 0$. It means drill pipe temperature equals to inlet drilling fluid temperature which is shown as T_{pi}.

Then eq. (2.33) becomes,

$$T_{pi} = K_1 + K_2 + T_s - \frac{G}{A} \tag{2.37}$$

At the bottom hole where $x = D$, temperatures of drill pipe and annulus are equal to each other.

$$K_1 e^{C_1 D} + K_2 e^{C_2 D} + GD + T_s - \frac{G}{A} = \left(1 + \frac{C_1}{A}\right) K_1 e^{C_1 D} + \left(1 + \frac{C_2}{A}\right) K_2 e^{C_2 D} + GD + T_s \tag{2.38}$$

$$\left(1 + \frac{C_1}{A} - 1\right) K_1 e^{C_1 D} + \left(1 + \frac{C_2}{A} - 1\right) K_2 e^{C_2 D} + \frac{G}{A} = 0 \tag{2.39}$$

$$C_1 K_1 e^{C_1 D} + C_2 K_2 e^{C_2 D} + G = 0 \tag{2.40}$$

$$C_2 = T_{pi} - C_1 - T_s + \frac{G}{A} \tag{2.41}$$

$$C_1 K_1 e^{C_1 D} + C_2 \left(T_{pi} - C_1 - T_s + \frac{G}{A}\right) e^{C_2 D} + G = 0 \tag{2.42}$$

15

$$C_1 K_1 e^{C_1 D} + \left(T_{pi} - T_s + \frac{G}{A}\right) C_2 e^{C_2 D} - K_1 C_2 e^{C_2 D} + G = 0 \tag{2.43}$$

$$K_1 (C_1 e^{C_1 D} - C_2 e^{C_2 D}) = \left(T_{pi} - T_s + \frac{G}{A}\right) C_2 e^{C_2 D} - G \tag{2.44}$$

$$K_1 = \frac{\left(T_{pi} - T_s + \frac{G}{A}\right) C_2 e^{C_2 D} - G}{(C_1 e^{C_1 D} - C_2 e^{C_2 D})} \tag{2.45}$$

$$K_1 = T_{pi} - K_2 - T_s + \frac{G}{A} \tag{2.46}$$

$$C_1 \left(T_{pi} - C_2 - T_s + \frac{G}{A}\right) e^{C_1 D} + K_2 C_2 e^{C_2 D} + G = 0 \tag{2.47}$$

$$\left(T_{pi} - T_s + \frac{G}{A}\right) C_1 e^{C_1 D} - K_2 C_1 e^{C_1 D} + K_2 C_2 e^{C_2 D} + G = 0 \tag{2.48}$$

$$K_2 (C_1 e^{C_1 D} - C_2 e^{C_2 D}) = \left(T_{pi} - T_s + \frac{G}{A}\right) C_1 e^{C_1 D} - G \tag{2.49}$$

$$K_2 = \frac{\left(T_{pi} - T_s + \frac{G}{A}\right) C_1 e^{C_1 D} - G}{C_1 e^{C_1 D} - C_2 e^{C_2 D}} \tag{2.50}$$

Solutions of equations are consistent with the Holmes et al. (1970) and Hasan et. al. (1991).

3. FLOW REGIMES AND RELATED EQUATIONS DURING DRILLING OPERATIONS

There are flow regimes when dynamic flow conditions are occurred. These flow regimes are laminar, turbulent and transition flow regimes. Heat transfer during drilling activities is affected by flow regimes. Drilling parameters play important role to determine the flow regimes. For annulus and drill string sections, flow regimes may be different. For geothermal wells, heat must be considered. Heat convection and heat conduction phenomena occur with dynamic flow conditions which is provided by drilling fluid. In this section, equations are shown to find Reynold number, mean velocity, equivalent drill pipe diameter, Prandtl number, convective heat transfer coefficient and overall heat transfer coefficient for annular and drill string sections.

3.1 Equations for Annulus Section

For annulus section, the flow regime is more complicated because of heterogeneity of zone. To determine flow regime through annulus, Reynolds number is used as follows (Eq. 3.1)

$$N_{Reynold,annulus} = \frac{928\rho V D_e}{\mu_p} \tag{3.1}$$

where ρ is the mud weight, V is mean fluid velocity, D_e is the equivalent drill pipe diameter (Bourgeyne et al., 1969) and μ_p is plastic viscosity of the drilling fluid.

$$D_e = 0,816(D_{wb} - Dpipe_{,OD}) \ \text{if} \ \frac{D_{pipe,OD}}{D_{wb}} > 0,3 \tag{3.2}$$

$$V = \frac{Q}{2,448(D_{wb}{}^2 - D_{pipe,OD}{}^2)} \tag{3.3}$$

where D_{wb} is well bore diameter, $D_{pipe,OD}$ is outer diameter of drillpipe and Q is the flow rate.

Prandtl number gives in Eq. (3.4) as ratio of ability of a fluid to transport momentum and to transport energy.

$$N_{Prandtl} = \frac{c_p}{\mu_p k_{mud}} \tag{3.4}$$

where c_p is the specific heat capacity of mud and k_{mud} is thermal conductivity of the drilling fluid.

Heat transfer coefficient across the annulus is given by Eq. (3.5). When $\frac{k_{mud}}{D_{wb}}$ is extracted from the eqution, Nusselt number across annulus is obtained.

$$h_{annulus} = 0,023[N_{Re,annulus}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{wb}} \tag{3.5}$$

To calculate heat balance equations, overall heat transfer coefficient across the annulus is given in Eq. (3.6)

$$U_A = \frac{1}{\left(\frac{1}{h_{annulus}}\right)+\left(\frac{r_{CI,4}}{k_{steel}}\right)\ln\left(\frac{r_{CO,4}}{r_{CI,4}}\right)+\left(\frac{r_{CI,4}}{k_{cement}}\right)\ln\left(\frac{r_{wb,4}}{r_{CO,4}}\right)+\left(\frac{r_{CI,3}}{k_{steel}}\right)\ln\left(\frac{r_{CO,3}}{r_{CI,3}}\right)+\left(\frac{r_{CI,3}}{k_{cement}}\right)\ln\left(\frac{r_{wb,3}}{r_{CO,3}}\right)+\cdots} \tag{3.6}$$

where r_{CI} is inner diameter of casing, r_{CO} is outer diameter of casing, k_{cement} is thermal conductivity of cement and k_{steel} is thermal conductivity of steel which is main material of casing and drill string.

3.2 Equations for Drill String Section

For drill string section, the flow regime is more reliable because of homogeneity of section. To determine flow regime through drill string, Reynolds number is used as follows (Eq. 3.7)

$$N_{Reynold,pipe} = \frac{928\rho V D_{pipe,ID}}{\mu_p} \tag{3.7}$$

where $D_{pipe,ID}$ is inner diameter of the drill pipe which can be classified according to its grades.

$$V = \frac{Q}{2,448D_{pipe,ID}^2} \text{ is the mean velocity through drill string.} \tag{3.8}$$

Heat transfer coefficient across the annulus is given by Eq. (3.9). When $\frac{k_{mud}}{D_{wb}}$ is extracted from the eqution, Nusselt number across drillstring is obtained.

$$h_{pipe} = 0,023[N_{Re,pipe}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{pipe,ID}} \tag{3.9}$$

To calculate heat balance equations, overall heat transfer coefficient across the drill string is given in Eq. (3.10)

$$U_p = \frac{1}{\left(\frac{1}{h_p}\right) + \left(\frac{D_{pipe,ID}}{k_{steel}}\right) \ln\left(\frac{D_{pipe,OD}}{D_{pipe,ID}}\right) + \left(\frac{D_{pipe,ID}}{D_{pipe,OD} h_{annulus}}\right)} \tag{3.10}$$

4. ANALYTICAL SOLUTIONS FOR EACH METHODS

In this chapter, analytical solutions are given for four geothermal wells. According to both methods that are Hasan and Kabir, Holmes and Swift; formation, drill string and annulus temperatures are calculated for each well at certain depths. To obtain results, mud outlet temperatures are used before cooling tower is started.

4.1 Analytical Solution of Holmes and Swift Method

Equations are solved by using Holmes and Swift method that is mentioned in chapter 3. Formation, annulus and drill string temperatures are obtained by this approach for different geothermal wells.

4.1.1 Analytical solution for well#1

The schematic demonstration is given for well#1 in Figure 4.1. The total depth is 1837m. Formation consists of metamorphic rocks where the lithology is marble. For all sections, tri cone bit is used. Drilling fluid is water-based mud.

Drilling, mud, drill string, formation and wellbore parameters are given respectively in table 4.1, 4.2 and 4.3 for well#1.

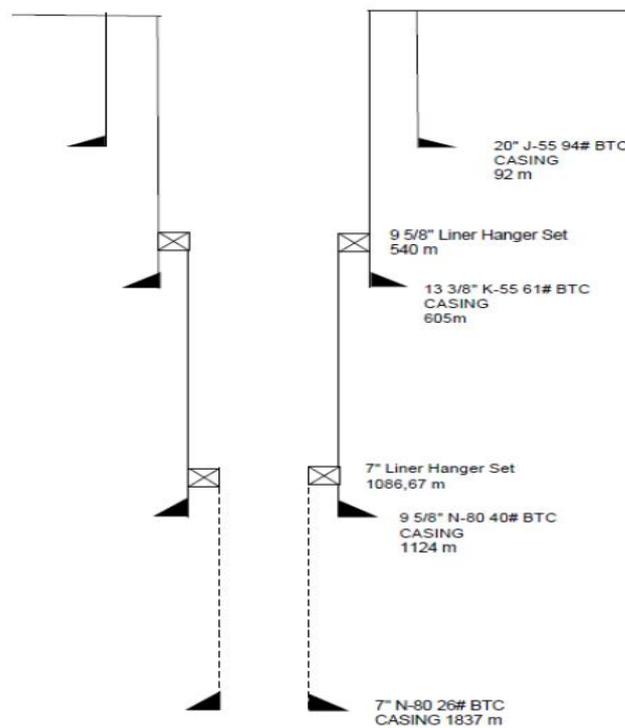**Table 4.1:** Table of drill string parameters for well#1.

$D_{pipe,OD}$ in	$D_{pipe,ID}$ in	D_{wb} in	H m	x m	r_{wb} in	k_{steel} $\dfrac{BTU}{°F.ft.hr}$
5	4,276	8 1/2	1838	1751	4 1/4	26,19

Table 4.2: Table of drilling and drilling fluid parameters for well#1.

Q	ρ	c_p	T_{pi}	μ_p	k_{mud}	t_{drill}	k_{cement}
gpm	$\dfrac{lb}{gal}$	$\dfrac{BTU}{°F.lb}$	$°F$	cp	$\dfrac{BTU}{°F.ft.hr}$	hr	$\dfrac{BTU}{°F.ft.hr}$
350	9,63	0,964	127,4	14	0,835	411,5	0,895

Table 4.3: Table of formation and wellbore parameters for well#1.

G	T_s	$k_{formation}$,	$c_{formation}$	$\rho_{formation}$
$\dfrac{°F}{ft}$	$°F$	$\dfrac{BTU}{°F.ft.hr}$	$\dfrac{BTU}{°F.lb}$	$ppcf$
0,0361	49	1,9	0,214	171,677

Figure 4.1: Schematic demonstration of well#1 diagram.

$$D_e = 0,816(D_{wb} - Dpipe_{,OD}) = 2,856 \; inches$$

$$\frac{D_{pipe,OD}}{D_{wb}} = 0,6 > 0,3$$

$$N_{Reynold,annulus} = \frac{928\rho \dfrac{Q}{2,448(D_{wb}{}^2 - D_{pipe,OD}{}^2)} D_e}{\mu_p} = 5361$$

Annular flow is turbulent because the Reynold number is greater than 3500 at the annulus.

$$N_{Prandtl} = \frac{c_p}{\mu_p k_{mud}} = 0,034$$

$$h_{annulus} = 0,023[N_{Re,annulus}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{wb}} = 6,76 \; \frac{BTU}{°F.ft^2.hr}$$

U_A

$$= \frac{1}{\left(\dfrac{1}{h_{annulus}}\right) + \left(\dfrac{r_{CI,4}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,4}}{r_{CI,4}}\right) + \left(\dfrac{r_{CI,4}}{k_{cement}}\right)\ln(\dfrac{r_{wb,4}}{r_{CO,4}}) + \left(\dfrac{r_{CI,3}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,3}}{r_{CI,3}}\right) + \left(\dfrac{r_{CI,3}}{k_{cement}}\right)\ln\left(\dfrac{r_{wb,3}}{r_{CO,3}}\right) + \cdots}$$

$$= 1,03 \; \frac{BTU}{°F.ft^2.hr}$$

$$N_{Reynold,pipe} = \frac{928\rho V = \dfrac{Q}{2,448 D_{pipe,ID}{}^2} D_{pipe,ID}}{\mu_p} = 20745$$

Flow is turbulent inside the drill string because the Reynold number is greater than 3500.

$$h_{pipe} = 0,023[N_{Re,pipe}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{pipe,ID}} = 39,66\frac{BTU}{°F.ft^2.hr}$$

$$U_p = \frac{1}{\left(\dfrac{1}{h_p}\right) + \left(\dfrac{D_{pipe,ID}}{k_{steel}}\right)\ln\left(\dfrac{D_{pipe,OD}}{D_{pipe,ID}}\right) + (\dfrac{D_{pipe,ID}}{D_{pipe,OD}h_{annulus}})} = 6,54\frac{BTU}{°F.ft^2.hr}$$

$$A = \frac{mc_p}{2\pi r_p U_P} = 25892 \qquad B = \frac{r_{wb}U_A}{r_p U_P} = 0,313$$

$$C_1 = \left(\frac{B}{2A}\right)\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 2,847E^{-5} \quad C_2 = \left(\frac{B}{2A}\right)\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = -1,64E^{-5}$$

$$C_3 = 1 + \frac{B}{2}\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 1,737 \qquad C_4 = 1 + \frac{B}{2}\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = 0,575$$

At H: 1838m,

$$K_2 = \frac{GA - [T_{pi} - T_s + GA]e^{C_1 H}(1 - C_3)}{e^{C_2 H}(1 - C_4) - e^{C_1 H}(1 - C_3)} = 1445{,}23 \qquad K_1 = T_{pi} - K_2 - T_s + GA = -433{,}1$$

At x: 1751m,

$$\frac{dT_a}{dx} = C_1 K_1 C_3 e^{C_1 x} + C_2 K_2 C_4 e^{C_2 x} + G = -0{,}0015$$

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - GA = 127{,}95\ °F$$

$$T_a = K_1 C_3 e^{C_1 x} + K_2 C_4 e^{C_2 x} + Gx + T_s = 128{,}41\ °F$$

$$T_f = 260{,}62\ °F$$

Bit depth is 1751m. At bit depth, inlet temperature of mud is 127,4 °F. Annulus temperature is greater than drillpipe temperature at bit depth. Formation temperature is 260,62 °F at bit depth.

4.1.2 Analytical solution for well#2

The schematic demonstration is given for well#2 in Figure 4.2. The total depth is 2260m. Formation consists of metamorphic rocks where the lithology is marble. For all sections, tri cone bit is used. Drilling mud is water-based mud. Drilling, mud, drill string, formation and wellbore parameters are given respectively in table 4.4, 4.5 and 4.6 for well#2.

Table 4.4: Table of drill string parameters for well#2.

$D_{pipe,OD}$ in	$D_{pipe,ID}$ in	D_{wb} in	H m	x m	r_{wb} in	k_{steel} $\dfrac{BTU}{°F.ft.hr}$
5	4,276	8 1/2	2260	2204	4 1/4	26,19

Table 4.5: Table of drilling and drilling fluid parameters for well#2.

Q gpm	ρ $\dfrac{lb}{gal}$	c_p $\dfrac{BTU}{°F.lb}$	T_{pi} °F	μ_p cp	k_{mud} $\dfrac{BTU}{°F.ft.hr}$	t_{drill} hr	k_{cement} $\dfrac{BTU}{°F.ft.hr}$
324	9,09	0,964	140	14	0,835	398,4	0,895

Table 4.6: Table of formation and wellbore parameters for well#2.

G	T_s	$k_{formation}$	$c_{formation}$	$\rho_{formation}$
$\dfrac{°F}{ft}$	$°F$	$\dfrac{BTU}{°F.ft.hr}$	$\dfrac{BTU}{°F.lb}$	$ppcf$
0,0517	43	1,9	0,214	171,677

$$D_e = 0,816(D_{wb} - Dpipe_{,OD}) = 2,856 \; inches$$

$$\frac{D_{pipe,OD}}{D_{wb}} = 0,6 > 0,3$$

$$N_{Reynold,annulus} = \frac{928\rho \dfrac{Q}{2,448(D_{wb}{}^2 - D_{pipe,OD}{}^2)} D_e}{\mu_p} = 4820$$

Annular flow is turbulent because the Reynold number is greater than 3500 at the annulus.

$$N_{Prandtl} = \frac{c_p}{\mu_p k_{mud}} = 0,034$$

$$h_{annulus} = 0,023[N_{Re,annulus}]^{0,8}[N_{Pr}]^{0,4} \frac{k_{mud}}{D_{wb}} = 6,2 \; \frac{BTU}{°F.ft^2.hr}$$

U_A

$$= \frac{1}{\left(\dfrac{1}{h_{annulus}}\right) + \left(\dfrac{r_{CI,4}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,4}}{r_{CI,4}}\right) + \left(\dfrac{r_{CI,4}}{k_{cement}}\right)\ln(\dfrac{r_{wb,4}}{r_{CO,4}}) + \left(\dfrac{r_{CI,3}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,3}}{r_{CI,3}}\right) + \left(\dfrac{r_{CI,3}}{k_{cement}}\right)\ln\left(\dfrac{r_{wb,3}}{r_{CO,3}}\right) + \cdots}$$

$$= 1,01 \; \frac{BTU}{°F.ft^2.hr}$$

$$N_{Reynold,pipe} = \frac{928\rho V = \dfrac{Q}{2,448 D_{pipe,ID}{}^2} D_{pipe,ID}}{\mu_p} = 18650$$

Flow is turbulent inside the drill string because the Reynold number is greater than 3500.

$$h_{pipe} = 0,023[N_{Re,pipe}]^{0,8}[N_{Pr}]^{0,4} \frac{k_{mud}}{D_{pipe,ID}} = 36,42 \frac{BTU}{°F.ft^2.hr}$$

$$U_p = \frac{1}{\left(\frac{1}{h_p}\right) + \left(\frac{D_{pipe,ID}}{k_{steel}}\right)\ln\left(\frac{D_{pipe,OD}}{D_{pipe,ID}}\right) + \left(\frac{D_{pipe,ID}}{D_{pipe,OD}h_{annulus}}\right)} = 6{,}01\,\frac{BTU}{°F.ft^2.hr}$$

$$A = \frac{mc_p}{2\pi r_p U_P} = 25332 \qquad B = \frac{r_{wb}U_A}{r_p U_P} = 0{,}336$$

$$C_1 = \left(\frac{B}{2A}\right)\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 3{,}045E^{-5} \quad C_2 = \left(\frac{B}{2A}\right)\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = -1{,}72E^{-5}$$

$$C_3 = 1 + \frac{B}{2}\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 1{,}77 \qquad C_4 = 1 + \frac{B}{2}\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = 0{,}564$$

At H: 2260m,

$$K_2 = \frac{GA - [T_{pi} - T_s + GA]e^{C_1 H}(1 - C_3)}{e^{C_2 H}(1 - C_4) - e^{C_1 H}(1 - C_3)} = 1977{,}30 \qquad K_1 = T_{pi} - K_2 - T_s + GA = -570{,}6$$
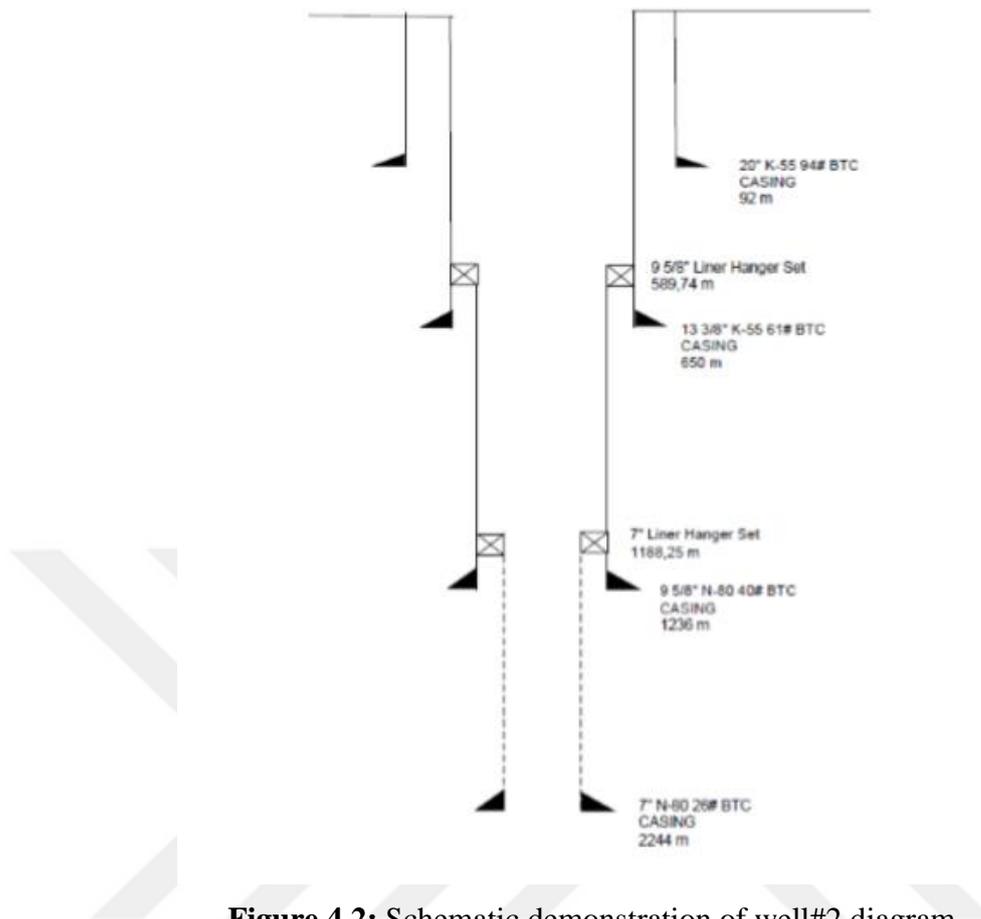
At x: 2204m,

$$\frac{dT_a}{dx} = C_1 K_1 C_3 e^{C_1 x} + C_2 K_2 C_4 e^{C_2 x} + G = -0{,}0036$$

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - GA = 142{,}17\,°F$$

$$T_a = K_1 C_3 e^{C_1 x} + K_2 C_4 e^{C_2 x} + Gx + T_s = 142{,}85\,°F$$

$$T_f = 424{,}8\,°F$$

Bit depth is 2204m. At bit depth, inlet temperature of mud is 140 $°F$. Annulus temperature is greater than drillpipe temperature at bit depth. Formation temperature is 424,8 $°F$ at bit depth.

Figure 4.2: Schematic demonstration of well#2 diagram.

4.1.3 Analytical solution for well#3

The schematic demonstration is given for well#3 in Figure 4.3. The total depth is 2432m. Formation consists of metamorphic rocks where the lithology is marble. For all sections, tri cone bit is used. Drilling mud is water-based mud. Drilling, mud, drill string, formation and wellbore parameters are given respectively in table 4.7, 4.8 and 4.9 for well#3.

Table 4.7: Table of drill string parameters for well#3.

$D_{pipe,OD}$	$D_{pipe,ID}$	D_{wb}	H	x	r_{wb}	k_{steel}
in	in	in	m	m	in	$\dfrac{BTU}{°F.ft.hr}$
5	4,276	8 1/2	2432	2091	4 1/4	26,19

Table 4.8: Table of drilling and drilling fluid parameters for well#3.

Q, gpm	ρ, $\dfrac{lb}{gal}$	c_p, $\dfrac{BTU}{°F.lb}$	T_{pi}, °F	μ_p, cp	k_{mud}, $\dfrac{BTU}{°F.ft.hr}$	t_{drill}, hr	k_{cement}, $\dfrac{BTU}{°F.ft.hr}$
310	9,2	0,964	131	14	0,835	385	0,895

Table 4.9: Table of formation and wellbore parameters for well#3.

G $\dfrac{°F}{ft}$	T_s °F	$k_{formation}$ $\dfrac{BTU}{°F.ft.hr}$	$c_{formation}$ $\dfrac{BTU}{°F.lb}$	$\rho_{formation}$ ppcf
0,0325	74	1,9	0,214	171,677

$$D_e = 0,816(D_{wb} - Dpipe_{,OD}) = 2,856 \ inches$$

$$\frac{D_{pipe,OD}}{D_{wb}} = 0,6 > 0,3$$

$$N_{Reynold,annulus} = \frac{928\rho \dfrac{Q}{2,448(D_{wb}{}^2 - D_{pipe,OD}{}^2)} D_e}{\mu_p} = 4668$$

Annular flow is turbulent because the Reynold number is greater than 3500 at the annulus.

$$N_{Prandtl} = \frac{c_p}{\mu_p k_{mud}} = 0,034$$

$$h_{annulus} = 0,023[N_{Re,annulus}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{wb}} = 6,05 \ \frac{BTU}{°F.ft^2.hr}$$

$$U_A = \frac{1}{\left(\frac{1}{h_{annulus}}\right)+\left(\frac{r_{CI,4}}{k_{steel}}\right)\ln\left(\frac{r_{CO,4}}{r_{CI,4}}\right)+\left(\frac{r_{CI,4}}{k_{cement}}\right)\ln\left(\frac{r_{wb,4}}{r_{CO,4}}\right)+\left(\frac{r_{CI,3}}{k_{steel}}\right)\ln\left(\frac{r_{CO,3}}{r_{CI,3}}\right)+\left(\frac{r_{CI,3}}{k_{cement}}\right)\ln\left(\frac{r_{wb,3}}{r_{CO,3}}\right)+\cdots} = 1,01 \ \frac{BTU}{°F.ft^2.hr}$$

$$N_{Reynold,pipe} = \frac{928\rho V = \dfrac{Q}{2,448D_{pipe,ID}{}^2} D_{pipe,ID}}{\mu_p} = 18060$$

Flow is turbulent inside the drill string because the Reynold number is greater than 3500.

$$h_{pipe} = 0{,}023[N_{Re,pipe}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{pipe,ID}} = 35{,}5\frac{BTU}{°F.ft^2.hr}$$

$$U_p = \cfrac{1}{\left(\dfrac{1}{h_p}\right) + \left(\dfrac{D_{pipe,ID}}{k_{steel}}\right)\ln\left(\dfrac{D_{pipe,OD}}{D_{pipe,ID}}\right) + \left(\dfrac{D_{pipe,ID}}{D_{pipe,OD}h_{annulus}}\right)} = 5{,}86\frac{BTU}{°F.ft^2.hr}$$

$$A = \frac{mc_p}{2\pi r_p U_P} = 25166 \qquad B = \frac{r_{wb}U_A}{r_p U_P} = 0{,}343$$

$$C_1 = \left(\frac{B}{2A}\right)\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 3{,}107E^{-5} \quad C_2 = \left(\frac{B}{2A}\right)\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = -1{,}74E^{-5}$$

$$C_3 = 1 + \frac{B}{2}\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 1{,}78 \qquad C_4 = 1 + \frac{B}{2}\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = 0{,}561$$

At H: 2432m,

$$K_2 = \frac{GA - [T_{pi} - T_s + GA]e^{C_1 H}(1 - C_3)}{e^{C_2 H}(1 - C_4) - e^{C_1 H}(1 - C_3)} = 1224{,}53 \qquad K_1 = T_{pi} - K_2 - T_s + GA = -349{,}62$$
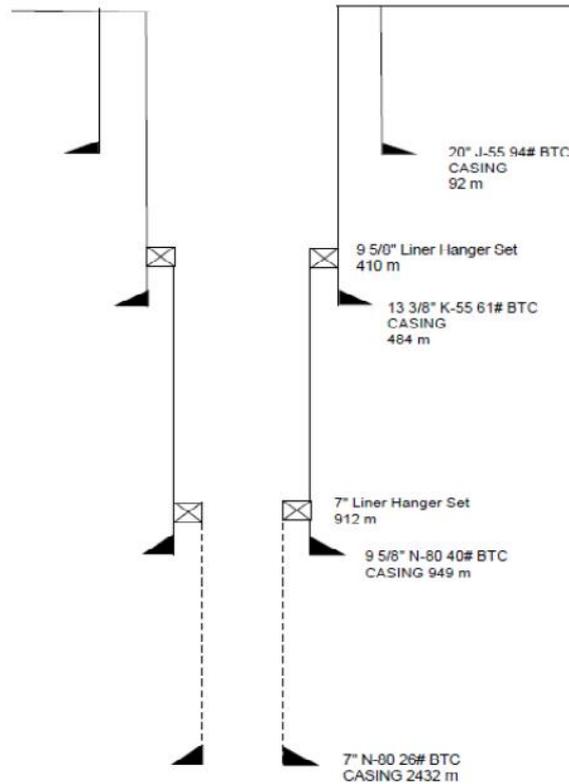
At x: 2091m,

$$\frac{dT_a}{dx} = C_1 K_1 C_3 e^{C_1 x} + C_2 K_2 C_4 e^{C_2 x} + G = -0{,}0021$$

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - GA = 132{,}82\,°F$$

$$T_a = K_1 C_3 e^{C_1 x} + K_2 C_4 e^{C_2 x} + Gx + T_s = 135{,}58\,°F$$

$$T_f = 294{,}54\,°F$$

Bit depth is 2091m. At bit depth, inlet temperature of mud is 131 $°F$. Annulus temperature is greater than drill pipe temperature at bit depth. Formation temperature is 294,54 $°F$ at bit depth.

Figure 4.3: Schematic demonstration of well#3 diagram.

4.1.4 Analytical solution for well#4

The schematic demonstration is given for well#4 in Figure 4.4. The total depth is 1206m. Formation consists of metamorphic rocks where the lithology is marble. For all sections, tri cone bit is used. Drilling mud is water-based mud. Drilling, mud, drill string, formation and wellbore parameters are given respectively in table 4.10, 4.11 and 4.12 for well#4.

Table 4.10: Table of drill string parameters for well#4.

$D_{pipe,OD}$ in	$D_{pipe,ID}$ in	D_{wb} in	H m	x m	r_{wb} in	k_{steel} $\dfrac{BTU}{°F.ft.hr}$
5	4,276	8 1/2	1206	1086	4 1/4	26,19

Table 4.11: Table of drilling and drilling fluid parameters for well#4.

Q	ρ	c_p	T_{pi}	μ_p	k_{mud}	t_{drill}	k_{cement}
gpm	$\dfrac{lb}{gal}$	$\dfrac{BTU}{°F.lb}$	$°F$	cp	$\dfrac{BTU}{°F.ft.hr}$	hr	$\dfrac{BTU}{°F.ft.hr}$
330	9,9	0,964	159,8	14	0,835	218,5	0,895

Table 4.12: Table of formation and wellbore parameters for well#4.

G	T_s	$k_{formation}$	$c_{formation}$	$\rho_{formation}$
$\dfrac{°F}{ft}$	$°F$	$\dfrac{BTU}{°F.ft.hr}$	$\dfrac{BTU}{°F.lb}$	$ppcf$
0,0385	70	1,9	0,214	171,677

$$D_e = 0,816(D_{wb} - Dpipe_{,OD}) = 2,856 \; inches$$

$$\frac{D_{pipe,OD}}{D_{wb}} = 0,6 > 0,3$$

$$N_{Reynold,annulus} = \frac{928\rho \dfrac{Q}{2,448(D_{wb}{}^2 - D_{pipe,OD}{}^2)} D_e}{\mu_p} = 5347$$

Annular flow is turbulent because the Reynold number is greater than 3500 at the annulus.

$$N_{Prandtl} = \frac{c_p}{\mu_p k_{mud}} = 0,034$$

$$h_{annulus} = 0,023[N_{Re,annulus}]^{0,8}[N_{Pr}]^{0,4} \frac{k_{mud}}{D_{wb}} = 6,74 \; \frac{BTU}{°F.ft^2.hr}$$

$$U_A = \frac{1}{\left(\dfrac{1}{h_{annulus}}\right) + \left(\dfrac{r_{CI,4}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,4}}{r_{CI,4}}\right) + \left(\dfrac{r_{CI,4}}{k_{cement}}\right)\ln\left(\dfrac{r_{wb,4}}{r_{CO,4}}\right) + \left(\dfrac{r_{CI,3}}{k_{steel}}\right)\ln\left(\dfrac{r_{CO,3}}{r_{CI,3}}\right) + \left(\dfrac{r_{CI,3}}{k_{cement}}\right)\ln\left(\dfrac{r_{wb,3}}{r_{CO,3}}\right) + \cdots} = 1,03 \; \frac{BTU}{°F.ft^2.hr}$$

$$N_{Reynold,pipe} = \frac{928\rho V = \dfrac{Q}{2,448D_{pipe,ID}{}^2} D_{pipe,ID}}{\mu_p} = 20688$$

Flow is turbulent inside the drill string because the Reynold number is greater than 3500.

$$h_{pipe} = 0,023[N_{Re,pipe}]^{0,8}[N_{Pr}]^{0,4}\frac{k_{mud}}{D_{pipe,ID}} = 39,57\frac{BTU}{°F.ft^2.hr}$$

$$U_p = \frac{1}{\left(\frac{1}{h_p}\right) + \left(\frac{D_{pipe,ID}}{k_{steel}}\right)\ln\left(\frac{D_{pipe,OD}}{D_{pipe,ID}}\right) + \left(\frac{D_{pipe,ID}}{D_{pipe,OD}h_{annulus}}\right)} = 6,53\frac{BTU}{°F.ft^2.hr}$$

$$A = \frac{mc_p}{2\pi r_p U_P} = 25878 \qquad B = \frac{r_{wb}U_A}{r_p U_P} = 0,313$$

$$C_1 = \left(\frac{B}{2A}\right)\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 2,852E^{-5} \quad C_2 = \left(\frac{B}{2A}\right)\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = -1,64E^{-5}$$

$$C_3 = 1 + \frac{B}{2}\left[1 + \left(1 + \frac{4}{B}\right)^{0,5}\right] = 1,74 \qquad C_4 = 1 + \frac{B}{2}\left[1 - \left(1 + \frac{4}{B}\right)^{0,5}\right] = 0,575$$

At H: 1206m,

$$K_2 = \frac{GA - [T_{pi} - T_s + GA]e^{C_1 H}(1 - C_3)}{e^{C_2 H}(1 - C_4) - e^{C_1 H}(1 - C_3)} = 1546,8 \qquad K_1 = T_{pi} - K_2 - T_s + GA = -460,68$$

At x: 1086m,

$$\frac{dT_a}{dx} = C_1 K_1 C_3 e^{C_1 x} + C_2 K_2 C_4 e^{C_2 x} + G = -0,00056$$

$$T_p = K_1 e^{C_1 x} + K_2 e^{C_2 x} + Gx + T_s - GA = 159,8\ °F$$

$$T_a = K_1 C_3 e^{C_1 x} + K_2 C_4 e^{C_2 x} + Gx + T_s = 160,1\ °F$$

$$T_f = 208,04\ °F$$

Bit depth is 1086m. At bit depth, inlet temperature of mud is 159,8 °F. Annulus temperature is greater than drillpipe temperature at bit depth. Formation temperature is 208,04 °F at bit depth.
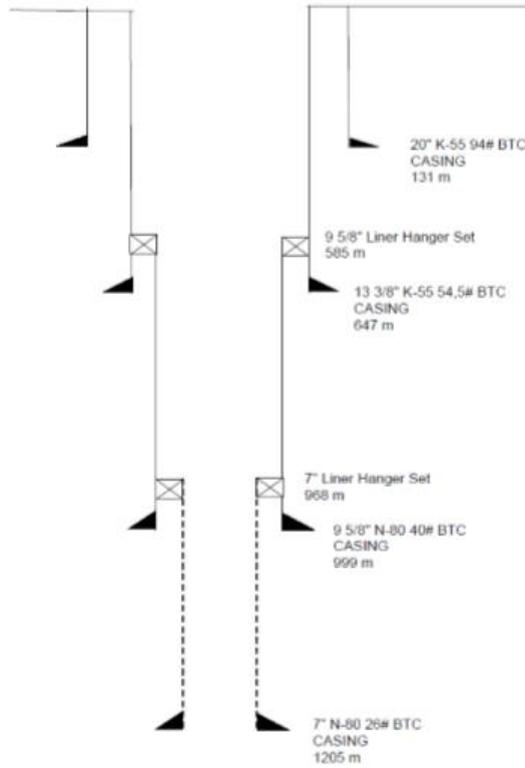
Figure 4.4: Schematic demonstration of well#4 diagram.

4.2   Analytical Solution of Hasan and Kabir Method

Equations are solved by using Hasan and Kabir method that is mentioned in chapter 2. Formation, annulus and drill string temperatures are obtained by this approach for geothermal wells. Lithology consists of %100 marble. Formation parameters are shown in table 4.13.

Table 4.13: Table of formation parameters.

k_m $\dfrac{BTU}{°F.ft.hr}$	k_f $\dfrac{BTU}{°F.ft.hr}$	c_m $\dfrac{BTU}{°F.lb}$	c_f $\dfrac{BTU}{°F.lb}$	ρ_m $ppcf$	ρ_f $ppcf$
1,9	1,9	0,214	0,214	171,67	171,67

$$\alpha = \frac{k_{formation}}{c_{formation}\rho_{formation}} = 0{,}0517 \ \frac{sq \ ft}{hr}$$

where α is the thermal diffusivity. The rate of heat transfer of a material can be measured which is from the hot end to the cold end.

4.2.1 Analytical solution for well#1

$$T_D = \frac{\alpha.(t_{drill})}{r_{wb}^2} = 169,66 \qquad T_D > 1.5$$

$$f(T_D) = (0,4063 + 0,5 \ln T_D)\left(1 + \frac{0,6}{T_D}\right) = 2,98$$

$$A = \frac{mc_p}{2\pi r_{wb}U_A}\left[1 + \frac{r_{wb}U_A f(T_D)}{k_{formation}}\right] = 130172,95$$

$$B = \frac{mc_p}{2\pi r_p U_P} = 25892,7$$

$$\lambda_1 = \frac{1}{2A}\left(1 - \sqrt{1 + \frac{4A}{B}}\right) = -1,38E^{-5} \qquad \lambda_2 = \frac{1}{2A}\left(1 + \sqrt{1 + \frac{4A}{B}}\right) = 2,148E^{-5}$$

At H: 1838m,

$$\theta = \frac{-[(T_{pi} + BG - T_S)\lambda_2 e^{\lambda_2 H} + G]}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = 1637,5$$

$$\beta = \frac{(T_{pi} + BG - T_S)\lambda_1 e^{\lambda_1 H} + G}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = -625,37$$

At x: 1751m,

$$\frac{dT_a}{dx} = \lambda_1(1 + \lambda_1 B)\theta e^{\lambda_1 x} + \lambda_2(1 + \lambda_2 B)\beta e^{\lambda_2 x} + G = -0,00098$$

$$T_p(x,t) = \theta e^{\lambda_1 x} + \beta e^{\lambda_2 x} + Gx - BG + T_S = 127,75\ °F$$

$$T_a(x,t) = (1 + \lambda_1 B)\theta e^{\lambda_1 x} + (1 + \lambda_2 B)\beta e^{\lambda_2 x} + Gx + T_S = 128,05\ °F$$

$$T_f = (T_a - T_p)\frac{A}{B} + T_a - A\frac{dT_a}{dx} = 257,4\ °F$$

At bit depth, annulus temperature is greater than drill pipe temperature. Formation temperature is 257,4 °F. Flowline temperatures show sharp increasing at beginning of 2000s. Then, slightly increasing can be seen.
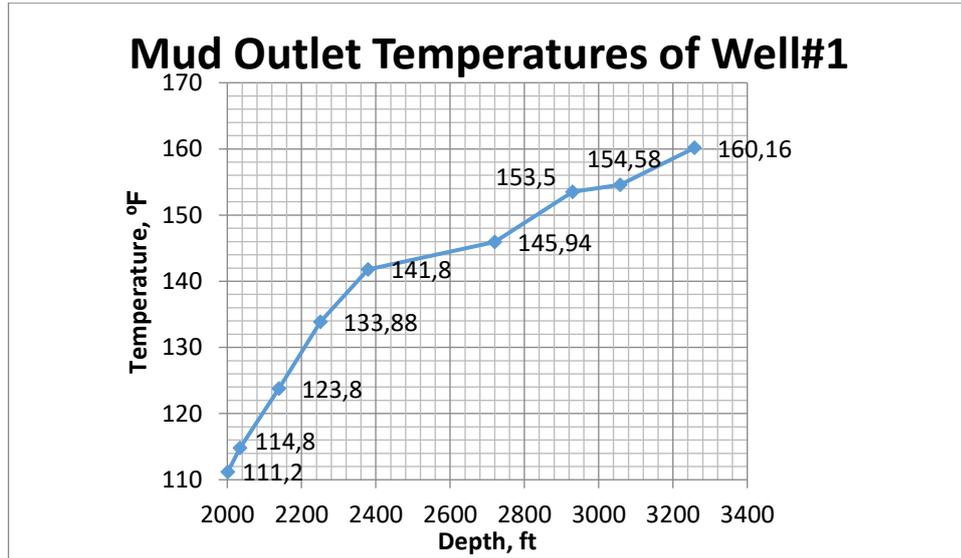
Figure 4.5: Mud outlet temperatures of well#1.

4.2.2 Analytical solution for well#2

$$T_D = \frac{\alpha.(t_{drill})}{r_{wb}^2} = 164,26 \qquad T_D > 1.5$$

$$f(T_D) = (0,4063 + 0,5\ln T_D)\left(1 + \frac{0,6}{T_D}\right) = 2,96$$

$$A = \frac{mc_p}{2\pi r_{wb}U_A}\left[1 + \frac{r_{wb}U_A f(T_D)}{k_{formation}}\right] = 117807,85$$

$$B = \frac{mc_p}{2\pi r_P U_P} = 25332,8$$

$$\lambda_1 = \frac{1}{2A}\left(1 - \sqrt{1 + \frac{4A}{B}}\right) = -1,454E^{-5} \qquad \lambda_2 = \frac{1}{2A}\left(1 + \sqrt{1 + \frac{4A}{B}}\right) = 2,303E^{-5}$$

At H: 2260m,

$$\theta = \frac{-[(T_{pi} + BG - T_S)\lambda_2 e^{\lambda_2 H} + G]}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = 2232,02$$

$$\beta = \frac{(T_{pi} + BG - T_S)\lambda_1 e^{\lambda_1 H} + G}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = -825,31$$

At x: 2204m,

$$\frac{dT_a}{dx} = \lambda_1(1 + \lambda_1 B)\theta e^{\lambda_1 x} + \lambda_2(1 + \lambda_2 B)\beta e^{\lambda_2 x} + G = -0,0023$$

$$T_p(x,t) = \theta e^{\lambda_1 x} + \beta e^{\lambda_2 x} + Gx - BG + T_S = 141,41 \text{ °}F$$

$$T_a(x,t) = (1 + \lambda_1 B)\theta e^{\lambda_1 x} + (1 + \lambda_2 B)\beta e^{\lambda_2 x} + Gx + T_S = 141,85 \text{ °}F$$

$$T_f = (T_a - T_p)\frac{A}{B} + T_a - A\frac{dT_a}{dx} = 416,86 \text{ °}F$$

Figure 4.6: Mud outlet temperatures of well#2.

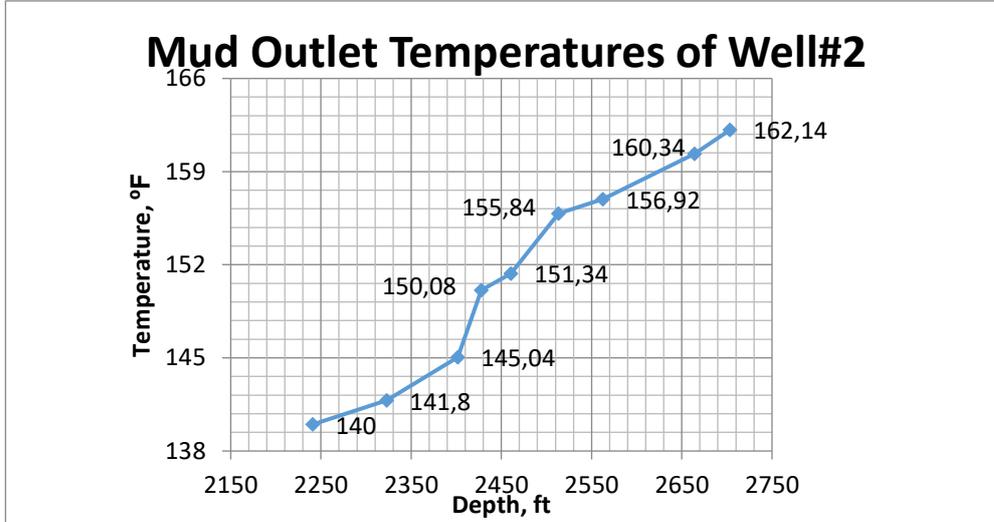At bit depth, annulus temperature is greater than drill pipe temperature. Formation temperature is $416,86 \text{ °}F$. Flowline temperatures show variable changings that happen linearly increasing.

4.2.3 Analytical solution for well#3

$$T_D = \frac{\alpha.(t_{drill})}{r_{wb}^2} = 158,73 \quad T_D > 1.5$$

$$f(T_D) = (0,4063 + 0,5 \ln T_D)\left(1 + \frac{0,6}{T_D}\right) = 2,95$$

$$A = \frac{mc_p}{2\pi r_{wb} U_A}\left[1 + \frac{r_{wb} U_A f(T_D)}{k_{formation}}\right] = 114160,47$$

$$B = \frac{mc_p}{2\pi r_P U_P} = 25166,4$$

$$\lambda_1 = \frac{1}{2A}\left(1 - \sqrt{1 + \frac{4A}{B}}\right) = -1,478E^{-5} \qquad \lambda_2 = \frac{1}{2A}\left(1 + \sqrt{1 + \frac{4A}{B}}\right) = 2,354E^{-5}$$

At H: 2432m,

$$\theta = \frac{-[(T_{pi} + BG - T_S)\lambda_2 e^{\lambda_2 H} + G]}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = 1381,14$$

$$\beta = \frac{(T_{pi} + BG - T_S)\lambda_1 e^{\lambda_1 H} + G}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = -505,23$$

At x: 2091m,

$$\frac{dT_a}{dx} = \lambda_1(1 + \lambda_1 B)\theta e^{\lambda_1 x} + \lambda_2(1 + \lambda_2 B)\beta e^{\lambda_2 x} + G = -0,0013$$

$$T_p(x,t) = \theta e^{\lambda_1 x} + \beta e^{\lambda_2 x} + Gx - BG + T_S = 132,18 \,°F$$

$$T_a(x,t) = (1 + \lambda_1 B)\theta e^{\lambda_1 x} + (1 + \lambda_2 B)\beta e^{\lambda_2 x} + Gx + T_S = 133,96 \,°F$$

$$T_f = (T_a - T_p)\frac{A}{B} + T_a - A\frac{dT_a}{dx} = 295,97 \,°F$$
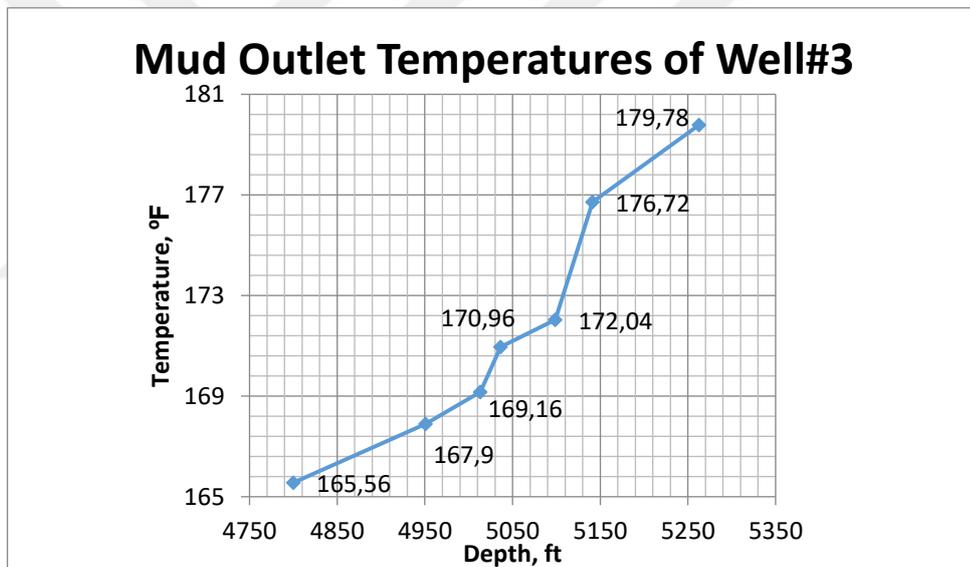
Figure 4.7: Mud outlet temperatures of well#3.

At bit depth, annulus temperature is greater than drill pipe temperature. Formation temperature is 295,97 °F. Flow line temperatures show slightly increasing at the beginning. According to graph, sudden increases are observed at the last sections during the drilling.

4.2.4 Analytical solution for well#4

$$T_D = \frac{\alpha.(t_{drill})}{r_{wb}^2} = 90,08 \quad T_D > 1.5$$

$$f(T_D) = (0{,}4063 + 0{,}5 \ln T_D)\left(1 + \frac{0{,}6}{T_D}\right) = 2{,}67$$

$$A = \frac{mc_p}{2\pi r_{wb}U_A}\left[1 + \frac{r_{wb}U_A f(T_D)}{k_{formation}}\right] = 124928{,}22$$

$$B = \frac{mc_p}{2\pi r_P U_P} = 25878{,}07$$

$$\lambda_1 = \frac{1}{2A}\left(1 - \sqrt{1 + \frac{4A}{B}}\right) = -1{,}403E^{-5} \qquad \lambda_2 = \frac{1}{2A}\left(1 + \sqrt{1 + \frac{4A}{B}}\right) = 2{,}204E^{-5}$$

At H: 1206m,

$$\theta = \frac{-[(T_{pi} + BG - T_S)\lambda_2 e^{\lambda_2 H} + G]}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = 1730{,}78$$

$$\beta = \frac{(T_{pi} + BG - T_S)\lambda_1 e^{\lambda_1 H} + G}{\lambda_1 e^{\lambda_1 H} - \lambda_2 e^{\lambda_2 H}} = -645{,}42$$

At x: 1086m,

$$\frac{dT_a}{dx} = \lambda_1(1 + \lambda_1 B)\theta e^{\lambda_1 x} + \lambda_2(1 + \lambda_2 B)\beta e^{\lambda_2 x} + G = -0{,}00037$$

$$T_p(x,t) = \theta e^{\lambda_1 x} + \beta e^{\lambda_2 x} + Gx - BG + T_S = 157{,}48\,°F$$

$$T_a(x,t) = (1 + \lambda_1 B)\theta e^{\lambda_1 x} + (1 + \lambda_2 B)\beta e^{\lambda_2 x} + Gx + T_S = 157{,}66\,°F$$

$$T_f = (T_a - T_p)\frac{A}{B} + T_a - A\frac{dT_a}{dx} = 205{,}58\,°F$$

At bit depth, annulus temperature is greater than drill pipe temperature. Formation temperature is 205,58 °F. Firstly, flowline temperatures increase during the drilling.
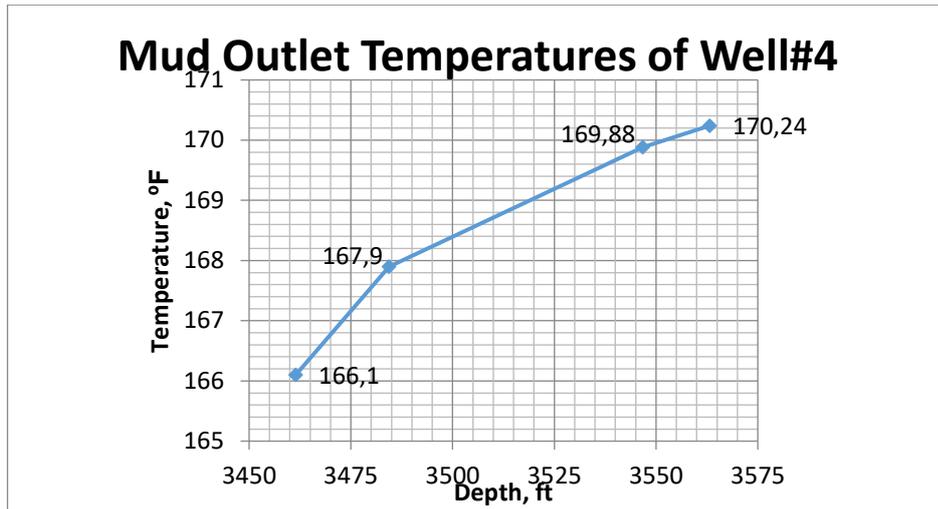
Figure 4.8: Mud outlet temperatures of well#4.

5. EVALUATION

In this study, analytical solutions are used to determine formation temperatures of different geothermal wells. In geothermal drilling, the most important parameter is formation temperature in terms of well producibility that provides energy for electricity.

Estimation of formation temperatures from drilling parameters can be done using heat balance equations across formation/annulus and annulus/drill string. So, partial differential equations are solved in this study. After solving of all relevant equations, annulus, drill pipe and formation temperatures can be obtained.

This study shows estimation of formation temperatures results for several geothermal fields. For further drilling operations at nearby locations, this could be offset data. To determine temperature distribution at those fields, obtained values can also be used.

From lithological properties and values of formation temperatures, it can be said that these wells are active geothermal wells. Temperature values are higher comparing to the other wells that have same depths.

All temperature values are computed before cooling tower was run because it leads to decrease in inlet temperature.

Active drilling time is included in this study. Because rotating time also affects the temperature to raise it.

There are some reasonable assumptions such as flow rate for some wells, plastic viscosity, OD and ID of drill pipe and mud weight for some wells because of limited data that are provided.

The comparison of the results is given in table 5.1, 5.2, 5.3 and 5.4.

Table 5.1: The results of well#1 for both models.

Well#1	Holmes and Swift	Hasan and Kabir
T_p, °F	127,95	127,75
T_a, °F	128,41	128,05
T_f, °F	260,58	257,40

Table 5.2: The results of well#2 for both models.

Well#2	Holmes and Swift	Hasan and Kabir
T_p, °F	142,16	141,41
T_a, °F	142,85	141,85
T_f, °F	424,80	416,86

Table 5.3: The results of well#3 for both models.

Well#3	Holmes and Swift	Hasan and Kabir
T_p, °F	132,81	132,18
T_a, °F	135,55	133,96
T_f, °F	293,55	295,97

Table 5.4: The results of well#4 for both models.

Well#4	Holmes and Swift	Hasan and Kabir
T_p, °F	157,50	157,49
T_a, °F	157,76	157,66
T_f, °F	206,46	205,58

When the results are compared, they have approximately same values for both models. So, results are similar. Formation temperatures which are obtained from this study are compatible with predicted formation temperatures.

For the first well, the results are given at 1751m. At this depth, annular temperature of the fluid is slightly greater than drill pipe temperature of the fluid for the both methods. Annular temperatures of the fluid are 128,41 °F and 128,05 °F according to Holmes and Swift, Hasan and Kabir's methods respectively. Drill pipe temperatures of the fluid are 127,95 °F and 127,75 °F. If the results were given at the bottom which is 1838m, annular and drill pipe temperatures would have been same. Formation temperatures are 260,58 °F and 257,40 °F. If the results were given at the bottom, formation temperatures would have been greater than these values.

For the second well, the results are given at 2204m. At this depth, annular temperature of the fluid is slightly greater than drill pipe temperature of the fluid for the both methods. Annular temperatures of the fluid are 142,85 °F and 141,85 °F according to Holmes and Swift, Hasan and Kabir's methods respectively. Drill pipe temperatures of the fluid are 142,16 °F and 141,41 °F. If the results were given at the bottom which is 2260m, annular and drill pipe temperatures would have been same. Formation temperatures are 424,80 °F and 416,86 °F. If the results were given at the bottom, formation temperatures would have been greater than these values.

For the third well, the results are given at 2091m. At this depth, annular temperature of the fluid is slightly greater than drill pipe temperature of the fluid for the both methods. Annular temperatures of the fluid are 135,55 °F and 133,96 °F according to Holmes and Swift, Hasan and Kabir's methods respectively. Drill pipe temperatures of the fluid are 132,81 °F and 132,18 °F. If the results were given at the bottom which is 2432m, annular and drill pipe temperatures would have been same. Formation temperatures are 293,55 °F and 295,97 °F. If the results were given at the bottom, formation temperatures would have been greater than these values.

For the fourth well, the results are given at 1086m. At this depth, annular temperature of the fluid is slightly greater than drill pipe temperature of the fluid for the both methods. Annular temperatures of the fluid are 157,76 °F and 157,66 °F according to Holmes and Swift, Hasan and Kabir's methods respectively. Drill pipe temperatures of the fluid are 157,81 °F and 157,49 °F. If the results were given at the bottom

which is 1206m, annular and drill pipe temperatures would have been same. Formation temperatures are 206,46 °F and 205,58 °F. If the results were given at the bottom, formation temperatures would have been greater than these values.

6. CONCLUSIONS

In this study, formation temperatures are estimated for different wells. To estimate these temperatures basic heat balance equation is used between sections where formation and wellbore are connected. Using differential equations, solutions are obtained for each well. To obtain those solutions, different approaches stated in the literature.

According to results, temperatures are similar with each other for both methods so, analytical approaches are valid for these geothermal wells. Formation temperature of the well#2 has the highest value comparing other wells. The reason is that well#2 is the deepest well where the last inlet mud temperature measurement was taken. It has also the highest geothermal gradient than the other wells. The well#4 has the lowest formation temperature value but, it has the highest drill pipe and annular temperature values. Heat losses of the well#4 may be lower than the other wells. It is the shallowest well. The well#3 is the deepest well where the drilling was finished but depth is lower than depth of well#2 where the last inlet mud temperature measurement was taken so, formation temperature of well#3 is lower than formation temperature of well#2. The well#1 has the lowest annular and drill pipe temperatures. Heat losses of well#1 may be higher than the other wells. Except well#2, wells have similar geothermal gradient values. It can be said that they are at the same regions. For those regions, wells may be drilled deeper to reach hot water sources.

This is the first study for geothermal wells. It has not been studied before. The importance of this study is leading assistance for further drilling operations. It can be used to determine well programs.

There are many assumptions in this study which are related wellbore and drilling parameters. For example, all casings are considered as closed. Casings are run from surface to bottom. If exact dynamic and static times are known, return line temperatures can be evaluated according to those different situations like circulation, tripping, connection and drilling. Temperature has lower values in static conditions

rather than in dynamic conditions. This situation affects the geothermal gradient estimation.

In conclusion, analytical solutions are used for estimation parameters which are regarding temperatures. It can be compared with downhole tools and logging operations. Obtained formation temperatures of this study are consistent with predicted formation temperatures.

REFERENCES

Aadnoy, B.S., and Karstad, E. (1997). Analysis of Temperature Measurements during Drilling. SPE 38603, San Antonio, Texas.

Ameen, M.M., Hasan, A.R., Kabir, C.S., and Kouba, G.E., (1996). Determining Circulating Fluid Temperature in Drilling, Workover and, Well – Control Operations SPE (24581).

Antics, M., Dumas, P., and Ungemach, P. (2013). Report on Geothermal Drilling. Presented at the GEOELEC.

Apak, E.C. (2006). A Study on Heat Transfer Inside the Wellbore During Drilling Operations. MSc thesis, The Graduate School of Natural and Applied Sciences Middle East Technical University, Ankara.

Aslanoglu, V,. Gul, S,. Senturk, E., and Tuzen, M.K. (2019). Estimation of Bottom Hole and Formation Temperature by Drilling Fluid Data: A Machine Learning Approach. Presented at 44th Workshop on Geothermal Reservoir Engineering, Standford, California.

Aytekin, A. (2016). Jeotermal Sondajlar. Retrieved from http://www.slideshare.net

Bengston, H. (2010). Convection Heat Transfer Coefficient Estimation. Retrieved from http://www.suncam.com, 1-40.

Bitlis, H., **Daskin, C., Ersoy, A., Hosbas, M., Kaya, T., Korkmaz, U., Oglu, I.S., Satkan, C., Simsek, F., and Ulgun, F.** (2011). Ankara, Turkey. Experiences in Geothermal Deep Well Drilling of TPIC in Turkey. GRC *Transactions,* Vol. 35.

Bobok, E., and Szarka, Z. (2012). Determination of the Temperature Distribution in the Circulating Drilling Fluid. Geosciences and Engineering, Vol. 1, No. 1, 37-47.

Bourgoyne Jr, A.T., Chenevert, M.E., Millheim, K.K, and Young Jr, F.S. (1986). Applied Drilling Engineering. Society of Petroleum Engineers, Richardson, TX.

Burgess, T.M., and Thompson, M. (1985). The Prediction of Interpretation of Downhole Mud Temperature While Drilling. SPE 14180, Las Vegas, USA.

Cermak, V., and Rybach, L. (1982). Thermal properties: Thermal conductivity and specific heat of minerals and rocks. Springer Verlak, Berlin, Heidelberg and New York. V/1a, 305-343.

Crain, E.R. (2015). Crain's Petrophysical Handbook. Measurements While Drilling and Geosteering. Retrieved from http://www.spec2000.net

Cromling, J. (1793). Geothermal Drilling in California. *Journal of Petroleum Technology,* SPE-AIME (4177). Presented at 43rd Annual Regional Fall Meeting, Bakersfield.

Espinoza, G., Garcia, A., Gonzalez-Partida, E., Santoyo, E., and Santoyo-Gutierrez, S. (2003). Convective heat-transfer coefficients of non-Newtonian geothermal drilling fluids. *Journal of Geochemical Exploration,* 249-255. doi : 10.1016/S0375-6742(03)00146-8.

Hasan, A.R., and Kabir, C.S. (1991). Heat Transfer During Two-Phase Flow in Wellbores: Part I – Formation Temperature. SPE (22866). Presented at the Annual Technical Conference and Exhibition, Dallas, Texas.

Holmes, C.S., and Swift, S.C. (1970). Calculation of Circulating Mud Temperatures. SPE-AIME (2318), Houston, Texas.

Horpestad, T. (2017). An investigation into the heat transfer process in petroleum wells, and a comprehensive modeling study investigating the temperature distribution in production wells. MSc thesis, Faculty of Science and Technology, University of Stavanger, Norway.

Kaya, T. (2012). Ankara, Turkey. Geothermal Project Development in Turkey – An Overview with Emphasis on Drilling. *GRC Transactions*, Vol. 36.

Korkmaz, S. (2014). Lecture Notes: Sondaj Tekniği (Sondaj Sıvıları/Sondaj Çamuru). Retrieved from http://jeolojitr.com

Laderian, A. (1999). Prediction of Temperature Profile in Oil Wells. Department of Mining Engineering Isfahan University, Isfahan, Iran. *International Journal of Engineering,* Vol. 13, No. 1, 77-89.

Midttomme, K., and Roaldset, E. (1999). Thermal conductivity of sedimentary rocks: uncertainties in measurement and modeling. *Geological Society London Special Publications.* doi: 10.144/GSL.SP.1999.158.01.04.

Moses, P.L. (1961). Geothermal Gradients. Presented at the spring meeting of the Southern District, Division of Production, Shreveport, L.A.

Raymond, L.R. (1969). Temperature Distribution in a Circulating Drilling Fluid. SPE-AIME (2320). Presented at SPE Symposium on Drilling and Rock Mechanics, Austin, Texas.

Santoyo-Gutierrez, E.R. (1997). Transient Numerical Simulation of Heat Transfer Processes During Drilling of Geothermal Wells. Telford Institute of Environmental - Systems, Water Resources Research Group, University of Salford, Salford, UK.

Steingrimsson, B. (2013). Geothermal Well Logging: Temperature and Pressure Logs. Rejkjavik, Iceland.

Subramanian, R.S. (2014). Heat Transfer in Flow Through Conduits. Department of Chemical and Biomolecular Engineering, Clarkson University.

Tekin, S. (2010). Estimation of the Formation Temperature from the Inlet and Outlet Mud Temperatures While Drilling Geothermal Formations. MSc thesis, The Graduate School of Natural and Applied Sciences Middle East Technical University, Ankara.

Xiao, Z.Q. (1987). The Calculation of Oil Temperature in a Well. SPE 17125, Richardson, TX, USA.

Yıldız, K. (2016). Taşınım Olayları. Sakarya University, Sakarya, Turkey.

Zhou, F. (2013). Research on Heat Transfer in Geothermal Wellbore and Surroundings. Berlin, Germany

CURRICULUM VITAE

Name and Surname   : **Oğuz Berk Evcimen**

Place and Date of Birth   : **Balıkesir - 29.08.1992**

E-Mail   : **evcimeno@itu.edu.tr**

EDUCATION

B.Sc.: 2016, Istanbul Technical University, Faculty of Mines, Petroleum and Natural Gas Engineering

WORK EXPERIENCE

- **Drilling Supervisor** : 2018, Turkish Petroleum International Company
- **Rig Manager** : (2016-2018), Safir Drilling Services