DANIEL JAKOB

HYBRID HEAT PUMP ANALYSIS

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THE OPTIMISATION OF A HEAT PUMP–GAS BOILER COMBINATION IN A RESIDENTIAL HOME

DANIEL JAKOB
(18409686)

Mechanical Engineering Master's (MEng.)
School of Mechanical and Materials Engineering
College of Engineering & Architecture
University College Dublin

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SUPERVISOR:
Prof. Donal Finn

COLLABORATOR:
Dr. Mohammad Saffari

EXAMINER:
Dr. Joe Bloggs

HEAD OF SCHOOL:
Prof. Kenneth Stanton

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LISTINGS

ACRONYMS

COP Coefficient of performance
HHS Hybrid heating system
ASHP Air source heat pump
PE Primary energy
SPF Seasonal performance factor

SCOP Seasonal coefficient of performance
RHI Renewable Heat Incentive
AWHP Air-Water Heat Pump
HP Heat Pump
HHPS Hybrid Heat Pump System
RES Renewable Energy Share
HDD Heating degree days

ABSTRACT

Short summary of the contents in English... a great guide by Kent Beck how to write good abstracts can be found here:

https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

Keywords: Hybrid heat pumps.

DECLARATION

I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

Belfield, Dublin 4, May 2023

Daniel Jakob

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— **knuth:1974** [**knuth:1974**]

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Put your acknowledgments here.

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1 Members of GuIT (Gruppo Italiano Utilizzatori di TeX e LaTeX)

Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

NOMENCLATURE

Physics Constants

c	Speed of light in a vacuum	$299\,792\,458\ \mathrm{m\,s^{-1}}$
G	Gravitational constant	$6.674\,30\times10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$
h	Planck constant	$6.626\,070\,15\times10^{-34}\ \mathrm{J\,Hz^{-1}}$

Number Sets

$\mathbb{C}$	Complex numbers
$\mathbb{H}$	Quaternions
$\mathbb{R}$	Real numbers

Other Symbols

ρ	Friction index
V	Constant volume

Part I

PREAMBLE

1

INTRODUCTION

1.1 CONTEXT

In Europe in 2022, the residential sector was responsible for 27% of final energy consumption [] Domestic water heating and space heating collectively account for close to 80% of a household's energy usage. []

Climate change has also directly affected heating and cooling design. Owen, American Society of Heating and Engineers highlight that for 1274 weather stations/observing sites worldwide with sound data between 1974 and 2006, the averaged design conditions (which are explained in Sec. 2.3) over all locations had changed by the following:

- the

In Ireland, the housing stock increased by just 0.4% between 2011 to 2016 [12]. Very few new houses are being constructed with the possibility for newer, more efficient space heating and/or hot water production systems and better, holistic insulation. A similar sentiment has been noted in other Western European countries, making this not a localised issue, but rather an international one [7, 9] .Thus, in order to reduce Primary energy (PE) consumption in any meaningful way, retrofits must be carried out on existing buildings. This includes adding insulation to attic spaces and/or walls of the house and the installation of more efficient heating systems. An advantage of HHS is that existing buildings presumably already have a heat generator, be it a gas boiler or otherwise, which can be easily integrated into a Hybrid heating system (HHS) with the addition of a Heat Pump (HP). Of course, plummbing works must be carried out and the HPitself has a relatively high barrier to entry in the form of a high upfront cost. Currently the Ireland do not give grants for the installation of HPas they do not deem them to be a renewable type of heat generator. This is partly true as HPdo use electricity to run.

The performance ASHP, or HPin general, is very different to that of a traditional gas condensing boiler. The performance of a HPis almost entirely determined by the outdoor temperature and climatic conditions. The performance of a HPis described by the Coefficient of performance (COP) of the unit. This measure varies troughout a heating season, day and even from minute to minute. A HPwith a COP of 3 for example, produces three units of heat energy for every unit of electricity supplied. This *extra* energy is being gathered from a renewable energy source — which in the case of AWHP is the external air. The amount of non-renewable energy consumed by HPat any given time depends on the Renewable Energy Share (RES) of the grid. According to Ireland, Ireland's RES for electricity is around 9.3%. This figure is epxected to increase in the coming years/decades as more wind turbines are installed, other renewable energy generators are built, the Celtic Interconnector subsea line between Ireland and France, and multiple non-renewable energy plants are decommisioned.

Since the COP of a Air source heat pump (ASHP) varies quite drastically over a heating season, the measure Seasonal coefficient of performance (SCOP) is often used to describe the performance of a Air-Water Heat Pump (AWHP)over a year or a heating season.

HP have over recent years become more popular throughout Europe

There are three main types of HP for space heating (i.e., not air-conditioning): AWHP, Ground-Water Heat Pumps and Hydro-Water Heat Pumps. Ground-Water HP acquire their heat energy by exploiting the heat contained within the Earth's soil. Soil, below a certain depth has a very consistent heat, only fluctating mildly seasonally. The added benefit of this type is that soil below a certain depth will not freeze, which would cause frosting like in AWHP. Hydro-Water HP gain their heat from water sources such as ponds, lakes or well-water. The temperature of water fluctuates far less than the ambient air temperature, meaning they do not extract as much energy as AWHP on warmer days, howerver, during warmer days, the heating load of a residential home is much less than the peak load. Conversely, during very cold days, the water remains much warmer than the air, which is very beneficial during those high-load spells. These two types of HP, due to their heat soruces, have their merits, however, it is also due to their heat sources that they are relatively obscure and not commonplace. Installing these types of HP is costly, complicated, time consuming and require permits to build. Due to these reasons, AWHP are the most common form of HP sold in Europe [1].

Frosting is detrminental to the performance of HP. During cold, humid weather, frost builds up on the evaporator coils on the outdoor component of the HP. Frosting dramatically lowers the heat conductivity between the coils and the ambient air, being essentially insulated by the frost. Frosting is a major concern in cool, humid climates, Ireland being one such climate.

A Hybrid Heat Pump System (HHPS) as opposed to monovalent systems, is a configuration of a HPin combination with a conventional gas boiler. During warmer days, the HPhas sufficient heating capacity to provide all the energy needed to heat a space, while being very efficient, while on colder days, it may be not economical or ecological to run the HP. During these peroids, the majority of the heating load is passed to the gas boiler, which is not affected by the ambient air temperature. A control system can be put in place to intelligently turn on and off the HPand gas boiler to better suit the current weather, for either economical or ecological reasons, or a weighted combination of the two. A (INSERT NAME FOR IT HERE) system is where the predefined external temperatures for turning on/off the HP/boiler are not coincident. This creates a temperature range wherein the HPand boiler are running simultaneously. This is the focus of this thesis: where lies the optimal crossover points for boiler-only operation, bivalent operation and HP-only operation, specifically for the Irish climate. This research has been carried out for other cliamte types. The Irish climate is unique in that the temperature range (during the heating season) is quite narrow, the humidity is quite high almost all year round (especially on the west coast) and the temperature is quite quite mild.

1.2 AIM

The aim of this thesis is to first, give an overview of the current state of research regarding HPand explain their operation including advantages, disadvantages, principle of operation and use cases.

1.3 MOTIVATION

The operation, control and performacnce of HHS consisting of AWHP and traditional gas boilers has been moderately studied in the literature. This type of heating system has been simulated and testing in-situ in countries such as China, Japan, Germany and other continental European countries, however, the research regarding efficient control of such a system in the Irish climate, namely a temperate oceanic climate, has not (or at the least only partially) been explored. Ireland has a very changeable and mild climate, but the characteristic of note is its consistently high humidity. Humidity and low temperatures are the bane of HPoperation and efficiency.

1.4 THE PROBLEM

1.5 THESIS LAYOUT

Chap. 2 is a literatuve review of the operation of HP, HHS,

2

LITERATURE REVIEW

2.1 OVERVIEW

HP work by harnessing the energy from low temperature sources such as air, water or the ground. Under ideal conditions, AWHP have extremely high COP in the 3.5 to 4.5 range. This is of course from their ability to harvest the aerothermal energy from the outside air. The main downfall of AWHP is that when the external air temperature is low, their COP is reduced significantly. Due to this inherent disadvantage, HP are essentially unfit be the sole space heating generator for almost all applications, depending on climates and design points. While HPhave the capacity to perform heating and cooling, this thesis and associated simulations do(es) not consider the cooling of a building or home, and therefore is only concerned with heating-seating heating. The space-heating radiators found in exisitng homes are not suitable for cooling [9], the cold water in the radiators does not cool the room effectively and condensation on the radiator surface may become and issue.

Because the efficiency of HP is so dependent on the outside air temperature, the measure of Seasonal performance factor (SPF) is typically used to characterise them when considering the performance over a certain heating peroid. The SPF represents the ratio of the total usefull energy produced by the HP during a heating season, to the seasonal electricity consumption. For example, an SPF of 3 would mean that over a given year, the HP produced 3 units of heating energy for every unit of electrical energy provided. Due to HP extracting renewable energy from the surrounding air, the SPF is (or should be) always higher than 1, and generally is above 3. EU legislation states that in order to be eligible for the Renewable Heat Incentive (RHI), a HP SPF must be above 2.5 [5].

HP come in many different heat capacities, from single kilo-watt units to extremely large units which can heat large multi storey office buildings. In residential home contexts, the largest HP generally available are almost 300 kW. If an ASHP were to be sized so large as to have the capacity to provide the entire heating envelope of a residential home during even the coldest expected temperatures, the ASHP would (aside from being prohibitively expensive), be so oversized that when temperatures are moderate, the HP would produce so much heat as to heat the space so quickly that it would have an extremely short on-off cycle [3]. Since the peak load for heating occurs for a very small number of hours during any given heating period, this would be very detrminental to the unit, specifically the condenser component. The frequent on-off cycling significantly reduces the longevity of the condenser, and would require replacement long before what would be expected. Many manufacturers suggest that the number of on-off cycles should not exceed 6 per hour. To avoid this issue, AWHP are specifically undersized. Various "design temperatures" can be calculated for a given location. For Dublin, the design temperature which covers 99.0% of the annual heating is −0.7 °C. AWHP are usually sized to meet a design temperature of 60%–70%, as opposed to more traditional space heaters, as is fruther explained in Sec. 2.3

HP tend to perform better when providing space heating through underfloor heating. This is partly due to underfloor heating being more efficient in general than other, more traditional space heating methods, namely hot-water radiators. Another reason more applicable to HP is that the (space heating) inlet water temperature for underfloor heating is much lower than radiators. This means the HP does not have to heat the circulating water as hot as it would with radiators. The temperature delta between water temperature inlet to the HP and the outlet is simply lower and therefore less energy has to be produced by the HP in the first place. However, retrofitting houses with underfloor heating is expensive and very intrusive to the building — as obviosuly (all) floors much be ripped up and coils must be placed and plumped — which discourages many homeowners from peforming this type of retrofit.

2.2 HEAT PUMP

[9] investigated the efficiency gains from the implementation of a HHS in a retrofitted house built in the 1970s. They compared this to other monovalent heating systems. A medium sized heat pump was used.

2.2.1 *Buffer Tank*

A buffer tank is a medium- to large-sized water vessel used in hydronic heating systems. It provides a large thermal inertia to the heating system-house system, which many small- to medium-sized houses, especially those with poor insulation, lack. Thermal inertia is a desired property of a building as rapid thermal fluctutations in ambient air are less of a concern when it comes to maintaining a comfortable thermal environment indoors. This effect is noticable in large office/district buildings with high thermal inertias and plays a significant role in heating-capacity selection [13]. Furthermore, a buffer tank provides a "hydraulic switch" and allows for heat generation and heat distribution to be in separate loops. This opens up the option to have differing flowrates between the heat generation and heat distribution loops.

Buffer tanks have been found, when sized correctly and with an appropriate control strategy, to have a positivie influence on the efficiency and performance on HHS [9, 16]. The controller is able to make use of the HP"most profitable working conditions" thanks to the presence of the buffer [6]. It has been found that when a buffer thank is present in the HPcircuit, SPF increases as the size of the HPdecreases [11]. Mugnini et al. confirmed this for all sizes of HPsimulated, the smallest buffer tank having a capacity of 200 L.

The larger a buffer tank in volume, the larger its energy storage capacity. However, with a larger volume, and naturally larger cylinder and surface area, comes greater heat loss, which seem to correlate almost linearly [9]. This could be justified if other performance factors such as SPF or load factor were positively affected to offset this loss in heat, however this does not seem to be the case according to [16] and Klein, Huchtemann and Müller, which also found only a moderate reduciton in on-off cycles with smaller tanks. This is partly to do with the thermal interia of the building and return temperature controller. Klein, Huchtemann and Müller found that the volume of the buffer tank had very limited effect on the system performance. Dongellini, Naldi and Morini sized their buffer tank just large enough such that the maximum nummber of on-off cycles was never greater than six per hour, resulting in a buffer tank with a volume of 79 L. This maximumm on-off cycle figure was chosen based off their HPmanufacturer guidelines. Daiken suggest [6]

2.2.2 *Frosting and Defrosting*

Frosting occurs in ASHP in colder ambient temperatures, typically from −15 °C to 6 °C [17], resutling in issues due to the frost build up. This specifically occurs when the surface temperature of the fins on the air-side heat exchanger are lower than the dew point of the of the air. Water droplets start to form and collect on the fins. When the temperatures is below freezing or close to it, the water droplets freeze to the fins and build up a frosting. Frost, unlike snow, which both form from the freezing of water droplets, is not loose and must be scraped off or melted off. It will not *fall off of* a surface like snow might. This layer of frost acts as a layer of insulation and restricts the heat exchanger from trannsferring heat from the ambient air. Since these fins are typically closely packed, if the layering of frost continues and progressively builds up, the airflow around the fins decreases and so does convective heat transfer to the ambient air, further exacerbating the issue of insulation. All of this is to say that when frosting occurs in ASHP, their performance declines severely. [19] found that the temperature of the air and surface of the fins, humidity, velocity of air are the main factors involved in frost formation.

Many treatments for frosting have been proposed and implemented into products. There is however no golden bullet solution, all of their advantages and disadvantages. Three main solutions are typically used when addressing the issue of frosting in ASHP.

- Simple on-off defrosting: the HPis simply switched off when too much frost has formed on the outdoor component. The performance has been degraded to such a point that it is now economically advantageous to turn off the HPand wait for the frost to melt away. This however, takes a long time and can negatively affect the thermal comfort of a home if no other heat production is used. The HPdoes not use any power during this off-cycle of course, retaining the COP of the HP— although, this may affect the overall system performance if a gas boiler needs to be used to provide the entire heating load of the home.

- Reverse cycle defrosting: this method is similar to the first method; the refrigerant is cycled in reverse and hot gas is forced into the heat exchanger. Recall that HPand refrigerators differ only in objective. The HPnow treats the outdoors as the "cold" sink and begins transferring heat from indoors to outdoors. Intuitively, one can see that this is quite detrminental to the performance of the HPas the house is being actively cooled in order to heat up the outdoor coils and fins to melt away the frost, and one cannot forget water's high thermal capacity... The intention in this method is to melt the frost much quicker than the first method, allowing the ASHPto being warming the home once again much earlier than the the simple on-off defrosting method.
- Resistive heating: electric resistive heaters are installed on/in the heat exchanger. This method works very well, quickly melting off frost and is a separate heating element to the HPand therefore does not interrupt the HPcycles. Resistive heaters are very expensive to run and negatively affect the COP of the HP.

[2] found that the reverse cycling method resulted in a higher COP than the other two methods.

2.3 HEATING DEGREE DAYS AND DESIGN TEMPERATURES

HDD is a measure of the difference between the outside temperature and the inside temperature. HDD are usually considered over a period of time, be it a month, heating season or entire year. A *base* temperature is chosen, typically around 12 °C to 21 °C which then determines when it is "cold" outside, or can be thought of as being the temperature above which heating is no longer considered to require heating. This base temperature can be chosen at will, and simply depends on what the person/institution deems to be *warm enoughh*. This measure can be used to quantitatively compare the heating demand of a given house in different locations/climates. The heating requirement of a specific building are directly proportional to the Heating degree days (HDD) [4].

To calculate the HDD for a certain day, three equations are used and are displayed from 2.1–**??**. Which equation to use is determined by the interaction between the base temperature and the maximum temperature recorded during that day.

$$\text{Degree days} = \begin{cases} t_{\text{base}} - \frac{1}{2}(t_{\text{max}} + t_{\text{min}}), & \text{if } t_{\text{max}} < t_{\text{base}} \\ \frac{1}{2}(t_{\text{base}} - t_{\text{min}}) - \frac{1}{4}(t_{\text{max}} - t_{\text{base}}), & \text{if } t_{\text{base}} > \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \\ \frac{1}{4}(t_{\text{base}} - t_{\text{min}}), & \text{if } t_{\text{base}} < \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \end{cases} \tag{2.1}$$

To co calculate the Monthly degree days however, only Eq. 2.1 is made use of. This total is found by summing the daily temperatures differences and can be seen in **??**.

$$\text{Montly degree days} = \sum_{\text{month}} \left[t_{\text{base}} - \frac{1}{2}(t_{\text{max}} + t_{\text{min}}) \right] \tag{2.2}$$

Environmental Design: CIBSE Guide A. has chosen a base temperature of 15.5 °C. *2009 ASHRAE Handbook: Fundamentals* used a base temperature of 18.3 °C and determined an annual HDD of 3135 °C d for Dublin Airport, IE, N53°26′ W6°15′. Using the online tool `Degree Days.Net` [18] with a base temperature of 15.5 °C, a HDD figure of 2072.3 °C d was obtained for the same location.

Design temperatures are a measure how many hours/days a specified condtion is exceeded. In the case of a heating design temperature, this would indicate how many days of the year or heating season are spent below a given temperature. *2009 ASHRAE Handbook: Fundamentals* notes that this measure does not give an indication of the freqeuncy or duration of these events, only a cummulative result is returned. According to *2009 ASHRAE Handbook: Fundamentals*, the 99.6% design temperature in Dublin Airport is −1.9 °C while the 99.0% design temperature is −0.7 °C. Traditionally, conventional gas boilers or resistive heaters were sized to design temperatures, meaning, for a chosen design temperature percentile (e.g., 99.0%), the heater could heat the building to thermally comfortable levels for 99% of the year, however during the 1% temperature lows, the heater would not be adaquate. This calculates to the heater being undersized for ~35 hours of the year.

$365 \times 24 = 8860\,\mathrm{h} \Rightarrow 99.0\% - ile = 8760(100 - 99.0) = 87.6$

In monovalent systems, the HPis sized in such a way as to be able to provided the entire heating load for a building at design conditions. This results in the HPbeing positively overdimensioned for the task [9].

The concept of a *design-day* can be used to design heating configurations for homes, especially when performing numerical simulations on a model of the system [15]. A design-day file is a special weather file created with design conditions in mind. Based on the design temperature parameter, ASHRAE, lays out a procedure to generate a 24-hour weather profile. These profiles represent the 0.4% to 99.6% extremes experienced for a particular location. This weather data is used in simulations to determine the minimum size for a heater required for a house (for these particular percentiles of course).

for the purposes of the simulation(s) concerning this thesis, the 0.4%-ile, and any cooling-nessecary-temperatures for that matter, are not of concern as cooling is out of scope.

The "heating duration curve" can be devised for a specific building for a specific climate. This chart plots the number of hours

Part II

MODEL AND RESULTS

3

METHODOLOGY

HHS

4 MODEL

HHS

5 SENSITIVITY ANALYSIS

[10]

6 TECHNO-ECONOMIC ASSESSMENT

[10]

7

CONCLUSIONS

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Part III

APPENDIX

A

APPENDIX TEST

Lorem ipsum at nusquam appellantur his, ut eos erant homero concludaturque. Albucius appellantur deterruisset id eam, vivendum partiendo dissentiet ei ius. Vis melius facilisis ea, sea id convenire referrentur, takimata adolescens ex duo. Ei harum argumentum per. Eam vidit exerci appetere ad, ut vel zzril intellegam interpretaris.

More dummy text.

A.1 APPENDIX SECTION TEST

Test: Tbl. A.1 (This reference should have a lowercase, small caps A if the option `floatperchapter` is activated, just as in the table itself → however, this does not work at the moment.)

Table A.1: Autem usu id.

LABITUR BONORUM PRI NO	QUE VISTA	HUMAN
fastidii ea ius	germano	demonstratea
suscipit instructior	titulo	personas
quaestio philosophia	facto	demonstrated

$$V = \frac{4}{3}\pi r^3 \tag{A.1}$$

$$= \eta_{\text{s, turbine}} \tag{A.2}$$

$$\operatorname{ch}(f_! \mathcal{F}^\bullet) \operatorname{td}(Y) = f_*(\operatorname{ch}(\mathcal{F}^\bullet) \operatorname{td}(X)) \tag{A.3}$$

Eq. A.1 Eqs. A.1 to A.3 Eqs. A.1 and A.3

A.2 ANOTHER APPENDIX SECTION TEST

Equidem detraxit cu nam, vix eu delenit periculis. Eos ut vero constituto, no vidit propriae complectitur sea. Diceret nonummy in has, no qui eligendi recteque consetetur. Mel eu dictas suscipiantur, et sed placerat oporteat. At ipsum electram mei, ad aeque atomorum mea. There is also a useless Pascal listing below: List. A.1.

More dummy textss.

Listing A.1: A floating example (`listings` manual)

```
for i:=maxint downto 0 do
begin
{ do nothing }
end;
```

COLOPHON

This document was typeset using the typographical look-and-feel `classicthesis` developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst's seminal book on typography *"The Elements of Typographic Style"*. `classicthesis` is available for both LaTeX and LyX:

`https://bitbucket.org/amiede/classicthesis/`

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