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Thermal Modelling of Loudspeaker Unit -and efficiency considerations

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A thermal model of a micro loudspeaker has been made and are documented in relation to thermal theory. The heat conduction and radiation between the voice coil and magnet are estimated. A linear thermal model are tested and adjusted according to thermal images of the micro transducer, steady state. The model is afterwards improved with a ventilation effect with a dependence of the diaphragm velocity. A comparison of a 6.5 inch driver and the modelled micro loudspeaker are made in relation to efficiency and size. The drawbacks by the small size are discussed with opportunities in the terms of efficiency and thermal aspects.

1 Introduction

The most common loudspeaker technology is electrodynamic loudspeakers. The sound is produced by a mechanical diaphragm making pressure changes in the air, sound waves. The diaphragm is driven by a voice coil in a magnetic field. Both conversion from electricity to mechanical movements followed by the conversion to pressure change in the air are ineffective [2]. The losses are primarily converted to heat in the voice coil.

The basic loudspeaker principal has not changed significant the last 100 years, but the size requirement has decreased drastic. The size matters for having a significant diaphragm size and to the enclosure size.

The loudspeaker in mobile phones today is used for ringing tones, playing music and other continues sounds. The displays have increased in size and made even less space for the loudspeaker. Not only for the audio performance is this problematic, by also for the thermal conditions. Thermal models of loudspeaker units can be used for understanding the mechanisms as input in the design process, or as protection in end user products.

Thermal models have been shown frequently in the literature [1,4] and the mechanisms of losses have been described. In this paper a micro loudspeaker is modelled and it is assumed that all power is lost in the voice coil. It is known that; eddy currents introduces losses in the magnetic structure [5], there are mechanical losses, and
a small amount of energy is converted to sound.

In this paper has a thermal model been developed and tested based on a micro loudspeaker, shown on figure 1. The transducer is 11 by 15 mm and has a free air resonance of 700 Hz, more data in table 1. For comparison is a 6.5 inch Scan-Speak 18W/8424G00 driver introduced. This is a midwoofer with a free air resonance of 54 Hz, more data in table 1.

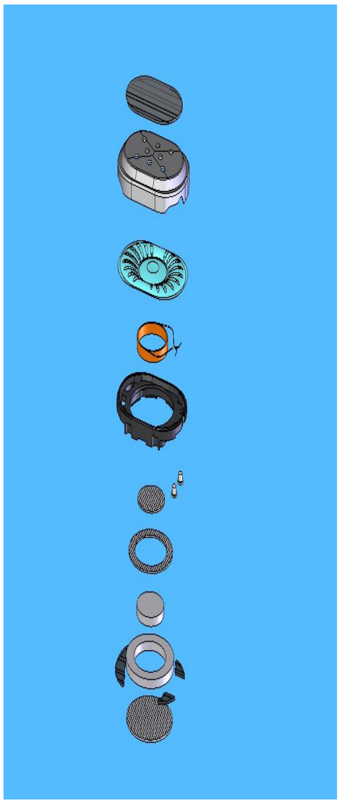


Figure 1: The micro loudspeaker

2 Efficiency of Loudspeakers

Loudspeakers are inefficient devices [1] wrote Douglas Button in 1990 in a scientific paper. Unfortunately has the focus at loudspeakers for home and portable audio not been at efficiency leading to even more inefficient loudspeakers. In the end products, has the focus been on reduced size, which is a problem for improving efficiency. The dominant inefficiency is the acoustic load at the diaphragm; the energy used to move the mechanical mass of the driver is very large compared to the acoustic output. In addition, the electro-mechanical conversion is inefficient (2).

The efficiency is found in the midband according to equation 1, [3].

$$Eff_{midband} = \frac{\rho \cdot Sd^2 \cdot B^2 \cdot l^2}{2 \cdot \pi \cdot c \cdot M_m^2 \cdot R_e} \tag{1}$$

ρ *density of air*
Sd *diaphragm surface*
B *magnetic flux in the magnetic gab*
l *length of the voice coil in the magnetic gab*
c *the speed of sound*
M_m *moving mass*
R_e *resistance of the voice coil*

Table 1: Loudspeaker parameters and efficiency

	Micro loudspeaker	6.5 inch	Difference
R_e	7.2 Ω	5.7 Ω	-21.%
BL	0.32 N/A	6.6 N/A	1963.%
M_m	23 mg	11.3 g	49030.%
Sd	0.65 cm^2	137 cm^2	20977.%
$Eff_{midband}$	0.0063%	0.63%	9900.%

The efficiency and relevant parameters are listed in table 1 and shall be set in relation to equation 1. The two chosen loudspeakers are very different in size. One is for mobile phones and the other for hi-fi use. The difference in diaphragm size and the possibility to apply a stronger motor in the big unit; much more efficient even though it is heavier.

3 Thermal Aspects of Loudspeaker Units

A simple viewpoint of the thermal aspects of a loudspeaker unit can be divided into two; mowing the power losses from the voice coil to the magnet and from the loudspeaker unit to the ambient air. This simplified viewpoint is not total correct, as example there are losses in the magnet, eddy currents, and air may flow by the voice coil cooling directly to the ambient.

Heat can be transferred in three ways: Conduction, radiation and convection. To view the effects of the individual heat transfers are the two sample loudspeaker investigated. The power transferred from the voice coil to the magnet is estimated. This estimate is based on the mechanical sizes of the voice coil and magnetic gab:

Table 2: Voice coil gab

	Magnetic gab hight	Free space in the front, between voice coil and magnetic gab	Free space in to the inside, between voice coil and magnetic gab
Micro loudspeaker	2 mm	0.14	0,14 mm
6,5 inch	5 mm /(10.2mm*)	0,33 mm	0,35 mm

*The centerpiece has not a center plate (“a strait line”) and the used height will be the voice coil height for the inside part of the magnetic gab.

3.1 Conduction

The conducted energy from the voice coil to the magnet passes through air. Even though the air is moved by the oscillating diaphragm the conduction is calculated from still air, the best isolator.

$$P_L = \frac{\lambda \cdot A \cdot \Delta T}{L} \qquad (2)$$

P_L	Heat Conduction [W]
λ	Thermal conductivity [W/(m ·K)]
A	Area [m^2]
ΔT	Temperature difference [K]
L	Length (thickness) [m]

Table 3: Calculated heat condition.

Heat conduction	Micro loudspeaker	6.5 inch unit
Power conducted from the voice coil to the magnet through air	377 [mW] $T_{voice\ coil}$= 165ºC T_{magnet}= 95ºC	7,3 [W] $T_{voice\ coil}$= 150ºC T_{magnet}= 70ºC

3.2 Radiation

In contrast to heat conduction the heat radiation is a nonlinear process. The temperature dependency is based on the absolute temperature to the fourth power, equation 3.

$$P_S = \varepsilon \cdot \sigma \cdot A_s \cdot T_1^4 - \varepsilon \cdot \sigma \cdot A_s \cdot T_2^4 \quad (3)$$

P_s	Radiated power [W]
ε	The emission factor
σ	Stefan-Boltzmanns constant (for blackbody) σ=5,67040·10^{-8} [W/m^2·K^4]
A_S	radiation area [m^2]
T_1	The temperature of the body [K]
T_2	The temperature of the body which is radiation to [K]

Table 4: Calculated heat radiation.

Heat radiated	Micro loudspeaker	6,5 inch unit
Power radiated from the voice coil to the magnet	30 [mW] $T_{voice\ coil}$= 165°C T_{magnet}= 95°C	611 [mW] $T_{voice\ coil}$= 150°C T_{magnet}= 70°C

The results in table 4 are based on an emission factor of 1, blackbody, which is too high making the results to large. Even knowing the calculation is overestimated the radiated power is relatively small.

3.3 Forced Convection

Forced convection or ventilation of the voice coil in the case of the loudspeaker. The flow design around the voice coil and the magnet is imported to enable the forced convection.

$$P_v = \rho \cdot c \cdot A \cdot v \cdot \Delta T \quad (4)$$

P_v	convected power [W]
ρ	density (air 1.205 kg/m^3)
c	specific heat capacity (air 1 J/g·K)
A	area to be cooled [m^2]
v	airspeed [m/s]
ΔT	temperature difference of air [K]

The forced convection is difficult to calculate because the airflow passing by the voice coil has to be found. Afterwards the heating of the passing air has to be calculated. The forced convection has therefor not been calculated.

3.4 Power Ratings

Power ratings are made by different standards or specified by the manufacture. The drivers power handling is specified by the IEC 60268-5 (ICE 17.1) a long time power handling which in details not can be published here. Both the major difference in size of the drivers and enclosures leads to differences in the thermal transport. The large driver has better ability to make forced ventilation, air cooling and large surface area to cool. The power difference is a factor of 100 times and the typical enclosure size is 1000 times (enclosures: 1 cm^3 and 10 liter). In thermal aspects will the used cooling air be cooler by improving the forced ventilation. The diaphragm area is 211 times bigger on the 6,5 inch driver leading to more airflow, better forced ventilation. The diaphragm velocity, the generator of the forced convection, is not only 10 times faster with its decade lower resonance frequency, but more than a factor 100 caused by the much greater sensitivity.

Table 5: Results; Rated power and calculated heat transfer.

Heat transferred	Micro loudspeaker	6,5 inch unit
Power conducted from the voice coil to the magnet through air	377 [mW]	7,3 [W]
Power radiated from the voice coil to the magnet	30 [mW]	1,2 [W]
Total power calculated	407 [mW]	8,5 [W]
Rated power (IEC 60268-5)	500 [mW]	50 [W]
Difference	93 [mW]	41,5 [W]

The dominant heat transfer is by conduction according to table 5 between the voice coil and the magnetic system. This makes a small gab between the voice coil and the magnet important for the loudspeakers thermal performance. The forced convection performance is set by the airflow design in the back of the loudspeaker unit and will be estimated in the modelling section. The forced convection is a very important cooling mechanism and that becomes even more important with increasing size. In table 5 are the theoretical results of heat conduction and radiation, forced convection not included. For the micro loudspeaker is the results 19% underestimated and by the 6,5 inch is it underestimated by 83%.

4 Thermal Model

The thermal model is optimized for the micro loudspeaker and the 6,5 inch driver has not been implemented. The model is verified from sinusoidal steady state test at different frequency. The diaphragm on the micro loudspeaker is made of thin plastic film and is therefore transparent for infrared radiation in the wavelength of 8-14 µm which a long wave thermal camera records. Figure 3 show a thermal image of the micro transducer driven with high amplitude.

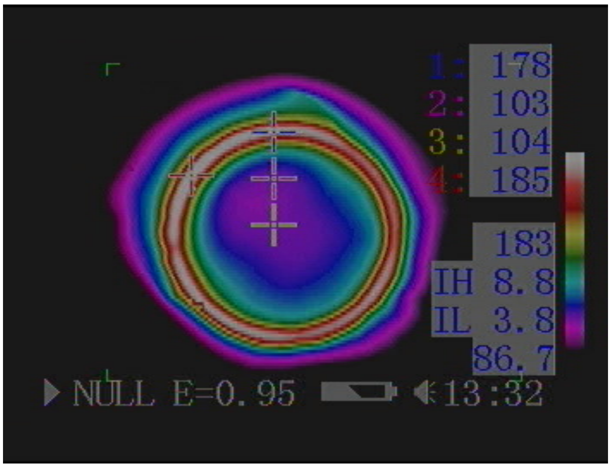


Figure 3: Thermal image of the micro loudspeaker. Marker 1 to 3 are placed on a vertical line starting with 1 from the top pointing at the voice coil. Maker 4 points at the maximum temperature.

4.1 Linear Thermal Model

The first tested and implemented model reflects the voice coil as a thermal capacity with a linear heat transfer to the thermal capacity of the magnet. The two heat capacities have been calculated from their weight. In this paper it is only the steady state result that is presented and thereby no reflections of the absolute size, but only the model structure and thermal resistance. Figure 4 shows the structure of the model where all losses are inputted to the voice coil and passed through the magnet before the output to the ambient.

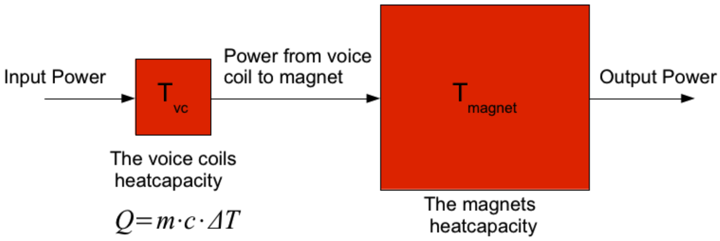


Figure 4: Second order linear thermal loudspeaker model.

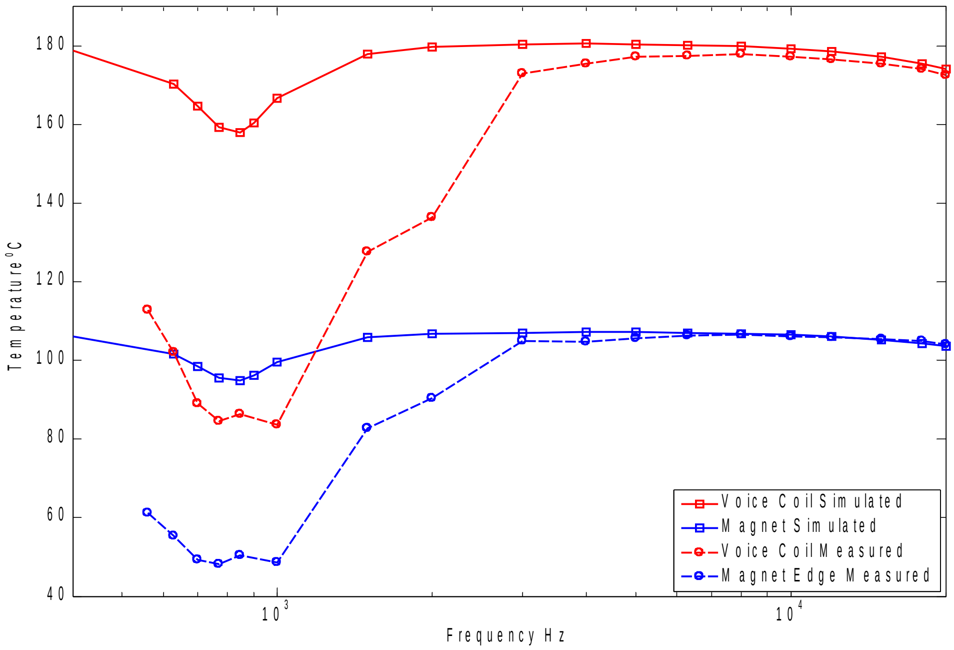
The model is implemented in a Matlab/Simulink environment where a loudspeaker model also is implemented for obtaining the power losses in the loudspeaker. The thermal model is based on equation 5 and 6.

First order thermal equation:

$$m \cdot c \cdot \frac{dT(t)}{dt} = P(t) \tag{5}$$

Heat Capacity:

$$Q = m \cdot c \cdot \Delta T \tag{6}$$



Input: $3V_{rms}$

Used thermal resistence:
$R_{vc\text{-}mag}$ = 9,5 mW/K
$R_{mag\text{-}amb}$ = 8,0 mW/K

Calculated thermal Resistence:
$R_{vc\text{-}mag}$ = 5,8 mW/K
(only conduction and radiation)

Figure 5: Linear thermal model results. Magnet and voice coil temperature. Resonance frequency 850Hz.

The thermal resistors are adjusted to fit the measured results at high frequencies. The heat transfer is better than calculated by conduction and radiation. This difference is believed to be explained be the movement of the air particles generating heat transport and the forced convection has also not been included. Around the resonance frequency has the model a poor fit. The physical cause is the ventilation effect generated by the diaphragm movement is an important cooling effect and it is also taken into account under the development of a loudspeaker.

4.2 Ventilation Model

The linear second order thermal model is extended with an air cooling effect as a function of the diaphragm velocity. This model is shown at figure 6 and becomes a nonlinear model. Several other models with different ventilation effects are known in literature [4] and as an example used in the Klippel Analyser.

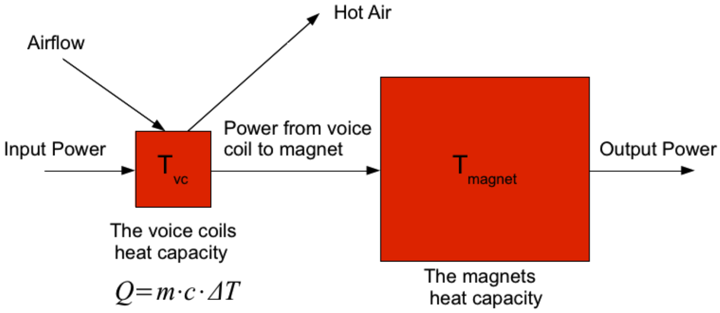


Figure 6: Second order thermal loudspeaker model with ventilation effect.

$$P_v = \rho_{air} \cdot m_{air} \cdot \Delta T \approx \tag{7}$$

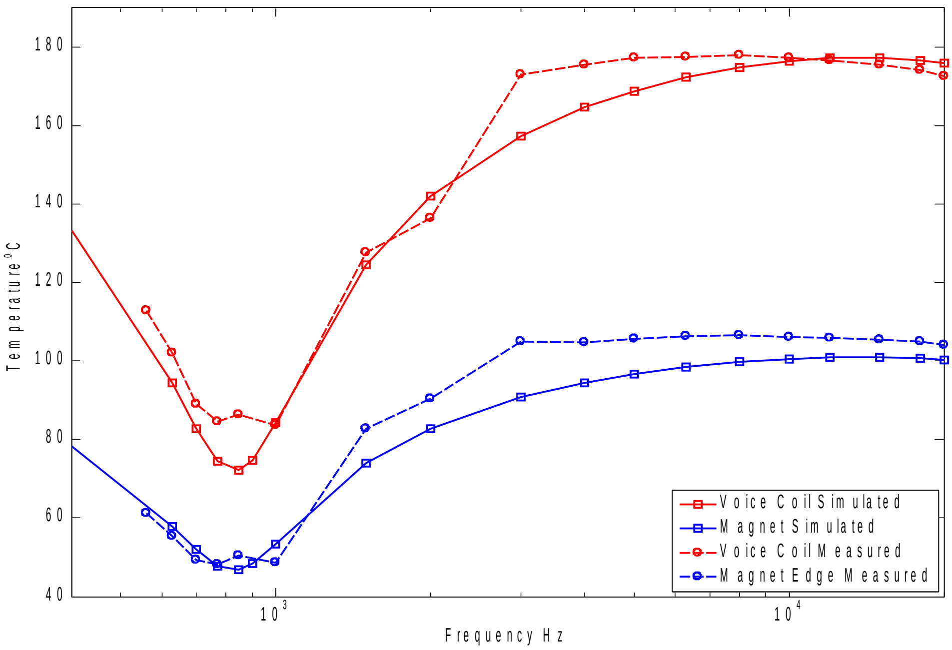
$$\rho_{air} \cdot c_{air} \cdot S_d \cdot \left| \frac{dx(t)}{dt} \right| \cdot \Delta T \tag{8}$$

Equation 7 describes the power moved by an air flow as a function of temperature change and air velocity. The air velocity by the voice coil is estimated as a function of normalized diaphragm velocity. The temperature difference is estimated from voice coil temperature (equation 9). The two estimates are compensated with a linear constant, equation 10.

$$\Delta T \neq T_{voice\,coil} - T_{ambient} \tag{9}$$

Ventilation Equation: Cooling power as function of voice coil temperature and diaphragm velocity:

$$P_v(t) = \rho_{air} \cdot c_{air} \cdot S_d \cdot \left| \frac{dx(t)}{dt} \right| \cdot A_{convection\,factor} \cdot (T_{voice\,coil}(t) - T_{ambiant}(t)) \tag{10}$$



Input: 3V_{rms}

Used thermal resistence:
$R_{vc\text{-}mag}$ = 8,5 mW/K
$R_{mag\text{-}amb}$ = 8,0 mW/K

Calculated thermal Resistence:
$R_{vc\text{-}mag}$ = 5,81 mW/K
(only conduction and radiation)

Figure 7: Thermal model with ventilation effect, results. Magnet and voice coil temperature. Resonance frequency 900Hz.

The thermal resistance has been adjusted knowing the ventilation effect has an influence at high frequencies where they were manually adjusted by the linear model. The flow convection factor, equation 10, has as well been manually adjusted. In the frequency range app. 2-9 kHz underestimates the model.

5 Discussion

A thermal model can be used as input for R&D of loudspeaker units and products with loudspeakers. It can also be used in end products as overheating protection. Today are most loudspeakers designed to withstand the power amplifier it is connected with a worst case signal. This designs focuses passive handling of breakdown problems by enable the loudspeaker to withstand high power levels over long time, which is not the case in more than 99% of the times. This design method decreases in many cases the efficiency and thereby the sound output.

5.1 Low frequency output from small enclosures

The focus in loudspeaker design is often the physical size of the loudspeaker. As the example shows are smaller loudspeaker devices less efficient. Not only does the small diaphragm make the design difficult but also the increasing resonance frequency of the bass driver. The low frequency output is often improved by adding mass to the driver or/and implement a ventilated system. Adding mass to the driver decreases the resonance frequency but also the efficiency. Instead a more efficient driver shall be developed and the low frequency output be boosted by DSP. The boosted frequency range is less efficient than the overall more efficient driver. A thermal model shall enable higher flexibilities in alternative designs.

6 Conclusions

A relative simple second order model with a ventilation effect can estimate the temperature in a micro loudspeaker. The ventilation effect is very important and shall be taken into account in the loudspeaker unit and the product where the loudspeaker is integrated into. The model is proposed to be used as active protection of the loudspeaker.

A short reflection on the size of loudspeakers and efficiency must make an engineer think; can we market and sell a large loudspeaker with good efficiency and sound quality in this wireless time-age?

References

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