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Thermal Control of CCD camera dedicated for autonomic astronomical observation working in earth environment

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ABBREVIATION

TEM – Thermo-electric module

ABSTRACT

Within the "Pi of the sky" project, several CCD cameras for astronomic observations have been developed and manufactured. Its thermal design consist of thermoelectric module with radiator and fan cooled heat sink. As spin-off project, new CCD camera for both scientific observations and monitoring is being developed. Its main features are high-sensitivity and low noise (3-5 electrons at 2Mhz). It will be equipped also with Digital Signal Processor, which will enable effective computing for pattern recognition. In paper, there are presented experimental and simulation results of previous generation cameras, which helped to understand key driven parameters impacting on CCD module temperature. Additionally, numerical simulation of new camera thermal model was developed and used to compare possible thermal designs.

KEYWORDS

CCD camera, thermal analysis, thermal design, thermoelectric module

INTRODUCTION

The ultimate goal of the "Pi of the Sky" apparatus is observation of optical flashes of astronomical origin and other light sources variable on short timescales, down to tens of seconds [1]. It observes mainly emission Gamma Ray Bursts (GBR), but also variable stars, novae, blazars, etc. This task requires an accurate measurement of the source's brightness (and it's variability) [2]. Observatories are placed in san Pedro de Atacama in Chile and in Spain.

Fig. 1. Four cameras on the stand

Within this project CCD cameras (K-20 models) were developed and manufactured. To decrease influence of noise below $16e^-$ at 2Mhz, it is necessary to cool down CCD module [3]. Thermal design consists of thermoelectric module with fan cooled radiator (Fig. 4). It allows to reach about -15°C at sensor (shown at Fig. 3) and 5-10s CCD exposures. Rest of camera's key parameters were listed in Tab. 1.

Fig. 2. Camera with baffle

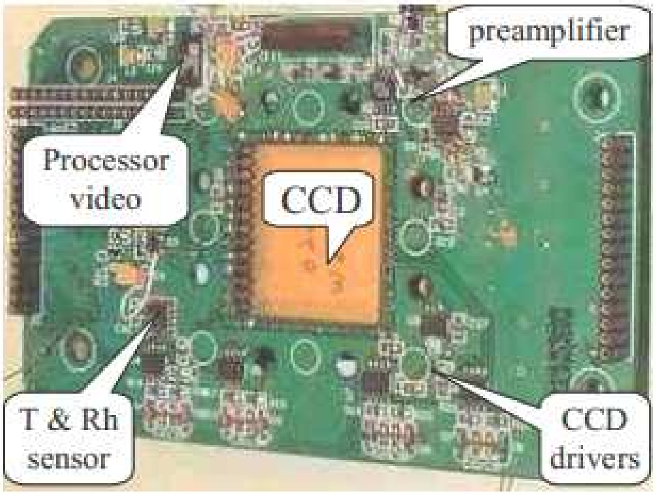


Fig. 3. CCD with electronics

System Design of "Pi of the sky project"
2 x 16 CCD cameras, 2000x2000 pixels, 5-10s exposures
optics: f=85mm, f/d=1.2 lenses, FOV ~22ox22o
covers 2 sr of the sky (=Glast LAT FoV> Swift BAT FoV)
data stream ~128 MB/s i.e. ~5 TB/night (USB 2.0 interface)
the whole night sky stored for ~12 hours
on-line analysis: automatic flash recognition in real time by a multilevel trigger system
fast reaction to GCN triggers
off-line analysis (next day): standard photometry and astrometry up to 14m (variables, asteroids)

Tab. 1. System design of "Pi of the sky project"

As spin-off project, new CCD camera (K-40 model) is being developed. Its main requirements is to be intelligent (image recognition), highly-sensitive and low-noise (below 3-5 electrons at 2Mhz). Built-in pattern recognition of the camera will be ensured by using digital processors for high-efficient computing. In terms of noise, there will be higher demand on CCD module temperature control than it was in K-20 model, because it is necessary to increase exposure time.

To meet requirements of new camera, more efficient thermal control technologies have to be implemented. Numerical studies were performed to compare different methods ([4], [5]). In next chapters, the results are presented.

Additionally, computer fluid dynamics (CFD) and heat transfer model of electronic box with signal processors were prepared. Study consists of two different air flow paths flow and its influence on temperature distribution and heat fluxes.

THERMAL DESIGN SOLUTION

In both models, K-20 and K-40, similar thermal design is implemented (In K-20 model heat sink is outside the casing). On Fig. 4 scheme of camera configuration is presented. Thermoelectric module is pumping heat (Q_{pump}) from CCD via cold finger to the fan cooled radiator. TEM is powered using Q_{tem} power. Both heat fluxes are spread to radiator and to camera casing (heat leakage Q_{res}). On analog CCD electronics and on digital electronics PCBs Joule's heat is generated. Heat is removed from camera by free convection cooling (Q_{conv}) and by forced convection (Q_{air}).

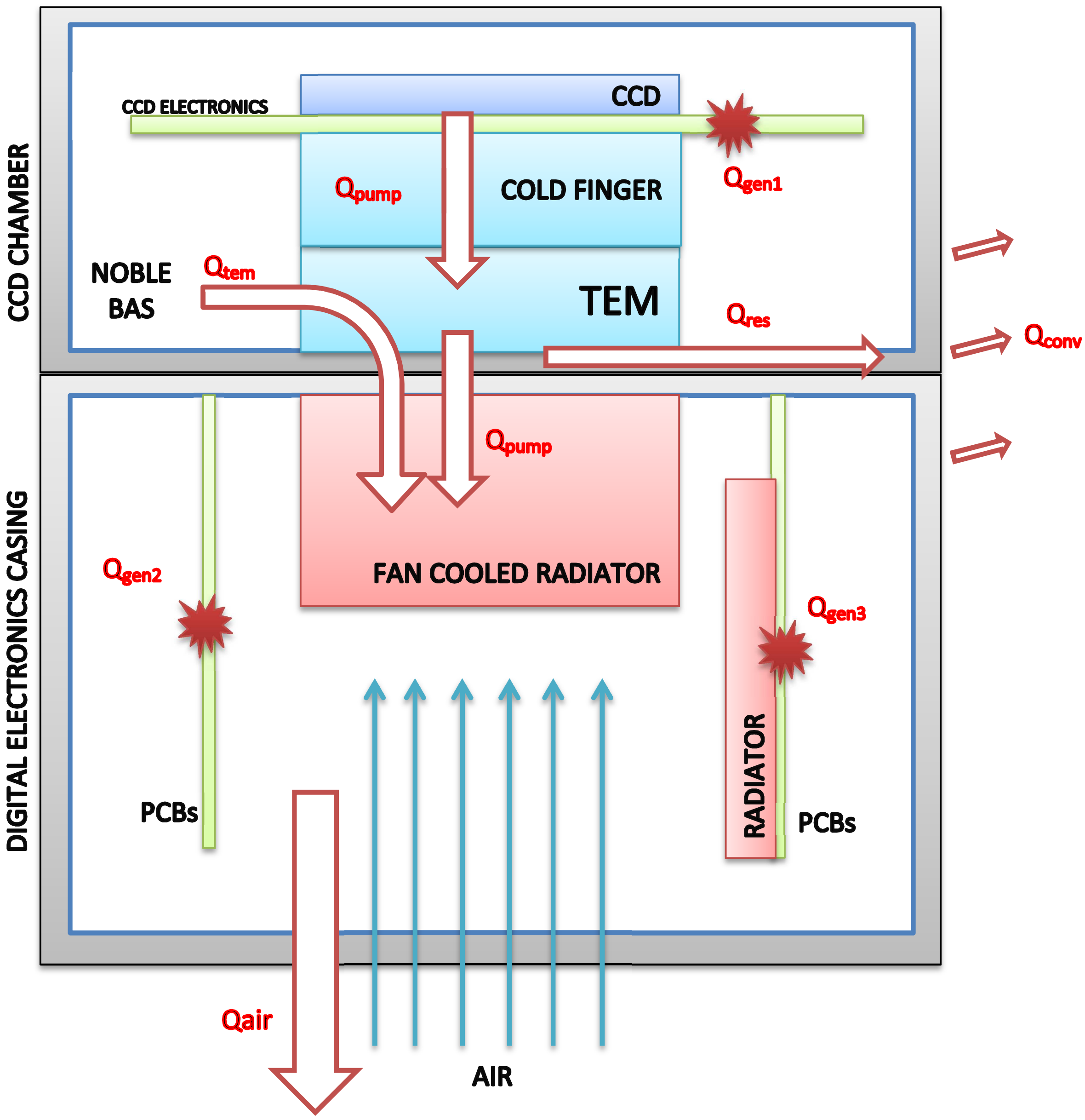


Fig. 4. Thermal design concept

PREVIOUS GENERATION OF CAMERAS – K-20 VERSION

Using CAD model of camera, 2D axisymmetric thermal model (Fig. 5) in COMSOL software was developed. Thermal design consists of thermoelectric module with heat sink. Main goal of thermal analyses was to identify key parameters determining the temperature of CCD module. Current solution enabled to reach about -20°C.

Mechanical components were modelled using heat equation:

$$\rho c_p \frac{\delta T}{\delta t} + \nabla * (-k\nabla T) = Q \tag{1}$$

Where:

Cp	Heat capacity at constant pressure	$\frac{J}{kg*K}$
Q	Heat source	$\frac{W}{m^3}$
T	Temperature	K
ρ	Density	$\frac{kg}{m^3}$
k	Heat conduction coefficient	$\frac{W}{m*K}$

Interior of casing was modelled with weakly compressible Navier-Stokes equations to simulate natural convection caused by thermal temperature differences:

$$\rho c_p \frac{\delta T}{\delta t} + \nabla * (-k\nabla T) = Q + q_s T + \rho c_p \vec{u} \nabla T \tag{2}$$

$$\rho \frac{\delta \vec{u}}{\delta T} + \rho * (\vec{u} * \nabla) u = \nabla * \left[-\mathrm{p} * \vec{I} + \eta * (\nabla \vec{u} + (\nabla \vec{u})^T) - \left(\frac{2\eta}{3}\right)(\nabla \vec{u}) \vec{I} \right] \tag{3}$$

$$\frac{\delta \rho}{\delta t} + \nabla * (\rho \vec{u}) = 0 \tag{4}$$

Where:

η	Dynamic viscosity	$Pa * s$
ρ	Density	$\frac{kg}{m^3}$
k	Heat conduction coefficient	$\frac{W}{m*K}$

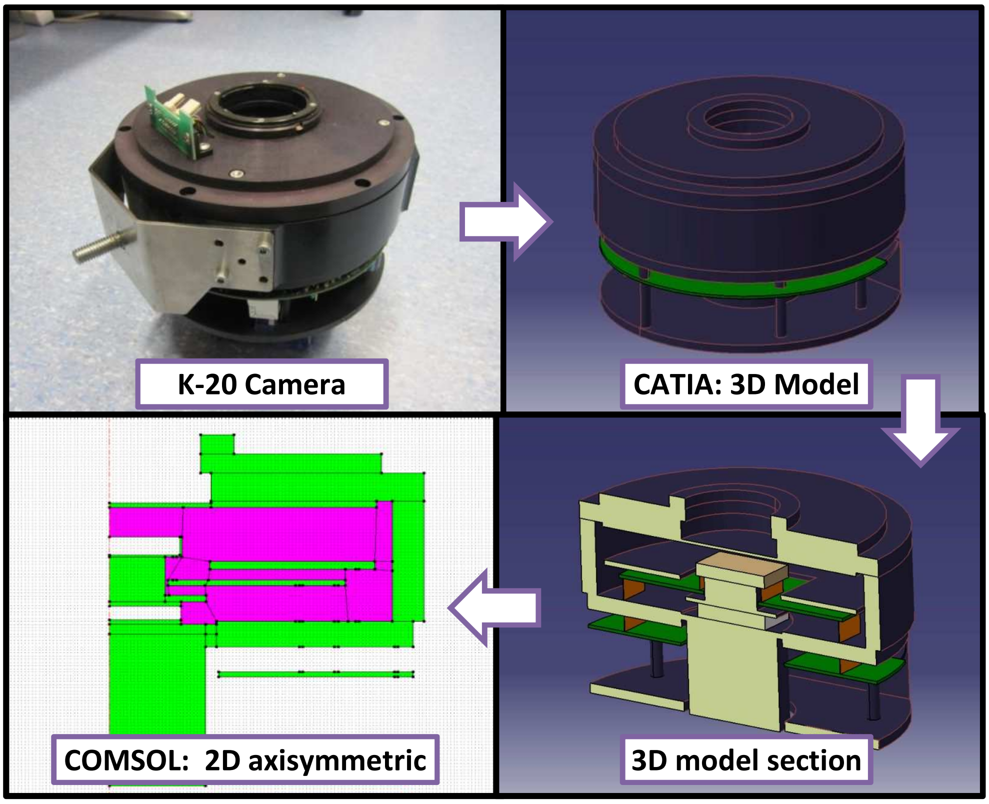


Fig. 5. Thermal model development phases

DESCRIPTION OF THE MODEL

In the Tab. 2 are presented elements of the camera with material associated with it.

No	Element	Material
1,2,4 ,6,8	Elements of the structure	PA6
6	Structure of shutter	PA6
3	Digital electronics PCB	FR4
5	Analog electronics PCB	FR4
7	Interior of camera	Air
9	Hot side of TEM	Ceramic
10	Cold side of TEM	Ceramic
11	Cold finger	PA6
12	CCD module	PA6

Tab. 2. List of elements

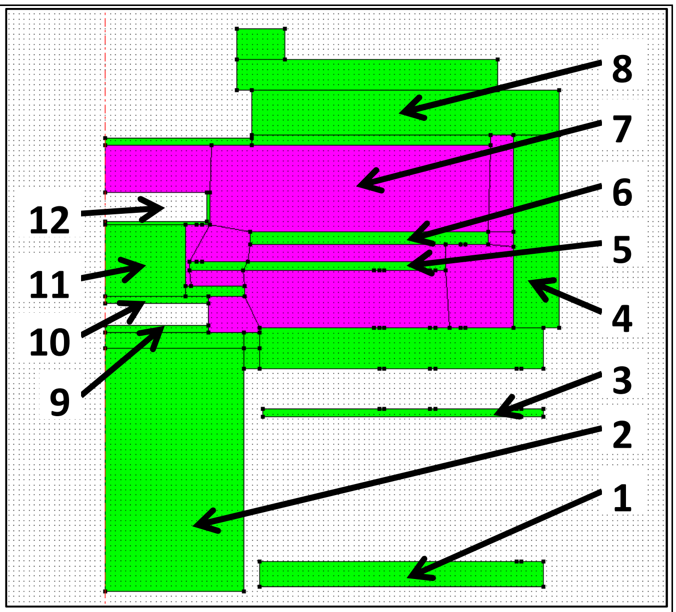


Fig. 6. Thermal model development phases

Boundary conditions on external walls were modelled using Newton's law of cooling:

$$\vec{n} * (-k * \nabla T) = q_0 + h * (T_{inf} - T) \qquad (5)$$

Where:

q_0	Normal heat flux	$\frac{W}{m^2}$
T_{inf}	Ambient temperature	K
T	Temperature	K
h	Heat conduction	$\frac{W}{m^2 * K}$
k	Heat conduction coefficient	$\frac{W}{m * K}$
$\vec{n}$	Normal vector	-

No	Type of boundary condition	Unit	
1	Konw. strumień ciepła	$\frac{W}{m^2}$	$-\vec{n} * (-k\nabla T) = h * (T_{inf} - T)$
2	Heat generation	$\frac{W}{m^3}$	$Q = 10W$
3	Heat generation	$\frac{W}{m^3}$	$Q = 5W$
4	External natural convection	$\frac{W}{m^2}$	Fan cooled heat sink (modelled with equation nr 5, h= 2000 $\frac{W}{m^2 * K}$).

Tab. 3. List of elements

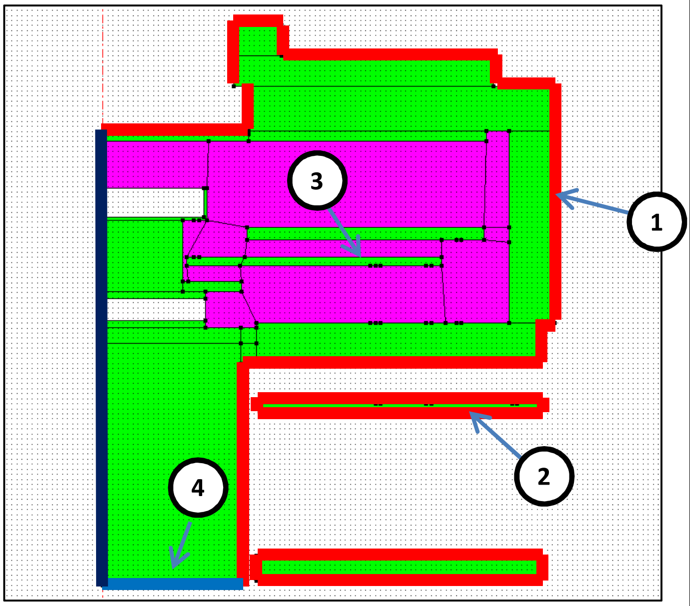


Fig. 7. Thermal model development phases

RESULTS AND ITS VALIDATION

Fig. 8 shows sample cameras' temperature distribution.

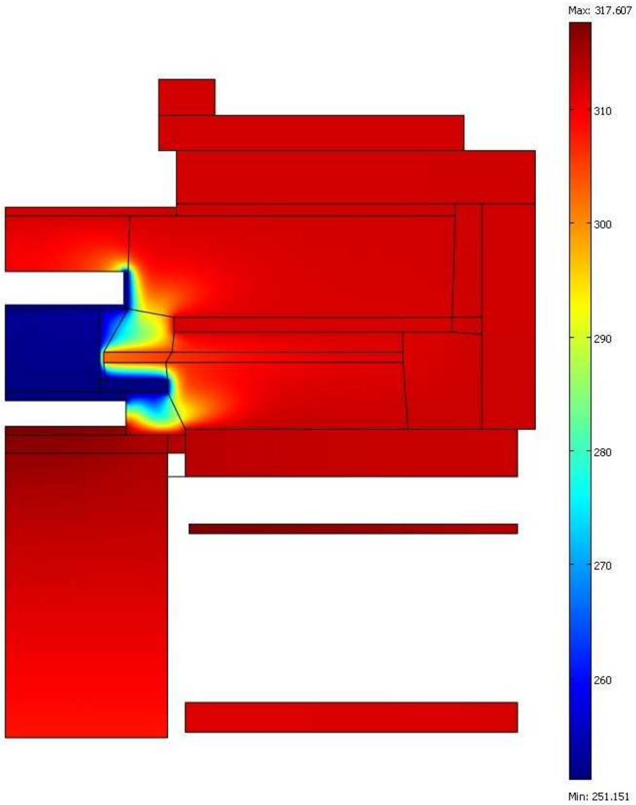


Fig. 8. Sample steady-state results

Analyses showed that there are few possibilities to decrease the temperature of CCD module. The most impacting factors are listed below:

- length of aluminium cylinder connecting hot side of TEM and heat sink (radiator and fan),
- length of cable connection between CCD itself and its electronics,
- type of TEM used. Version in K-20 was 78W power consuming with refrigeration power up to 65W if the temperature difference between hot and cold side is 0°C and 0W with maximum difference equals to 60-70°C (all values are dependent on hot side temperature).

The presence of vacuum inside the casing is not influencing much CCD temperature. This was reason for not using vacuum in new camera – (noble gas is sufficient).

Thermal model was validated by tests performed in climatic chamber. On Fig. 9, there are presented time-dependent temperatures for experimental and numerical results. Thermoelectric module was powered-off after 1200s during the test. It was proved that model have uncertainties equals to 5K.

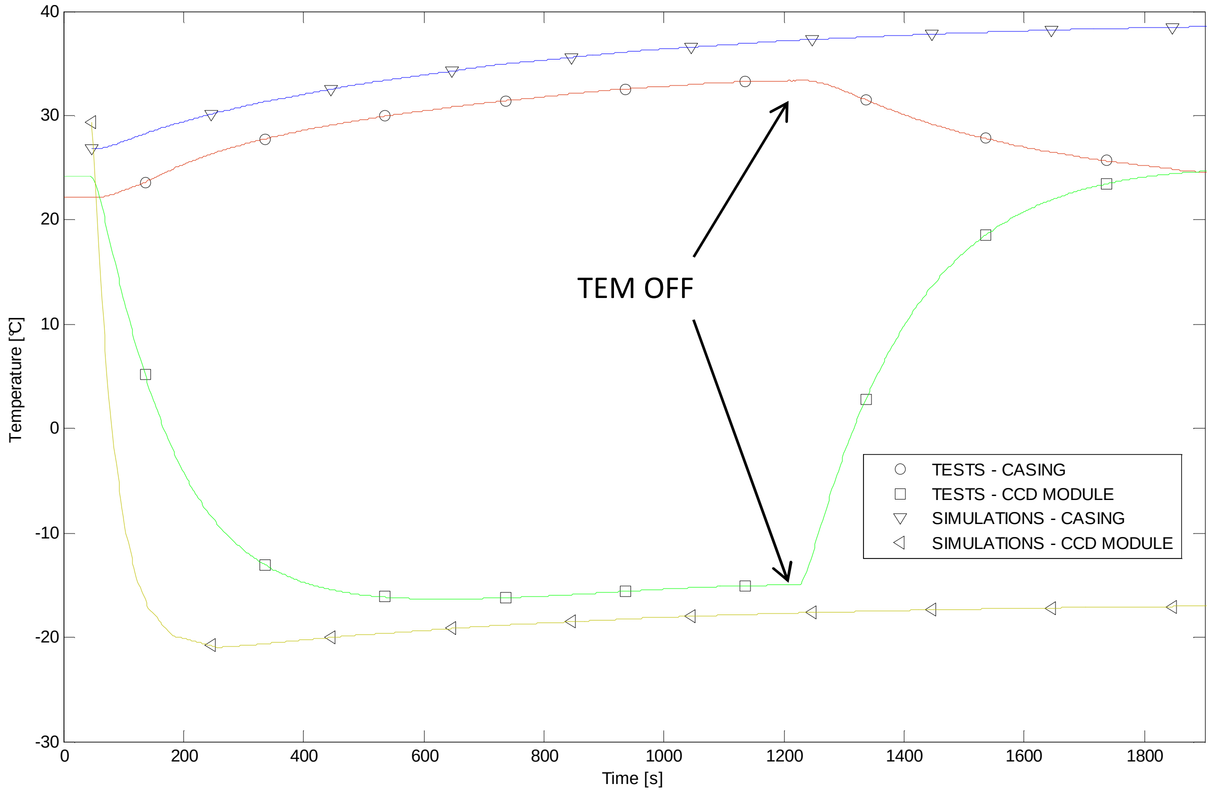


Fig. 9. Comparison of experimental and numerical results

NEW CAMERA – K-40 VERSION

Basing on K-20 camera model, new version is being developed. Conclusions from thermal analyses performed at the previous model, were included in new design. Thermal model was divided into 2 smaller: part with CCD module and electronic box with signal processors (both showed on Fig. 10). They were simulated separately, but included results from other.

K-40 THERMAL ANALYSES RESULTS

In the Tab. 4 there are presented results for different refrigeration methods. Multi-stage thermoelectric cooler gives lowest temperatures on CCD module. It is caused by high possible temperature differences on its both hot and cold sides. Very efficient heat sink on hot side of TEM is crucial.

Case	CCD temperature [°C]	Hot side of TEM [°C]	Temp. difference [°C]
Classical TEM, Fan cooled radiator with heat pipes	-15.4	57.2	73.6
Classical TEM, Water cooling	-27.6	36.5	65.0
Three-stage TEM	-25.8	70.4	97.2
Three-state TEM with efficient heat sink	-49.6	46.5	97.1

Tab. 4. Results of simulation for different refrigeration methods

To compare different cases of geometry configuration inside the electronic box, indicator presented below was used:

$$n = \frac{\dot{V}_{total}}{\dot{V}_{fan}}$$

Where:

$\dot{V}_{total}$	$flow\ rate\ TO\ camera$	$\frac{m^3}{s}$
$\dot{V}_{fan}$	$flow\ rate\ TO\ fan$	$\frac{m^3}{s}$

It helps to assess, how many hot air is moving back to fan instead leaving the electronic box.

Two configurations were studied: case A without tube regulating the flow and case B with the tube.

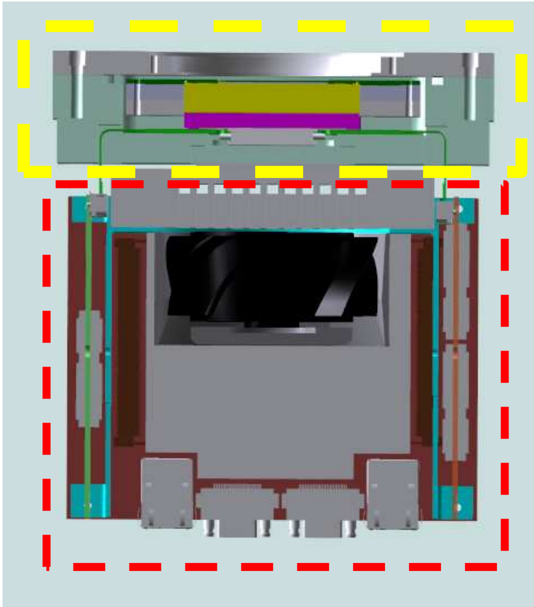
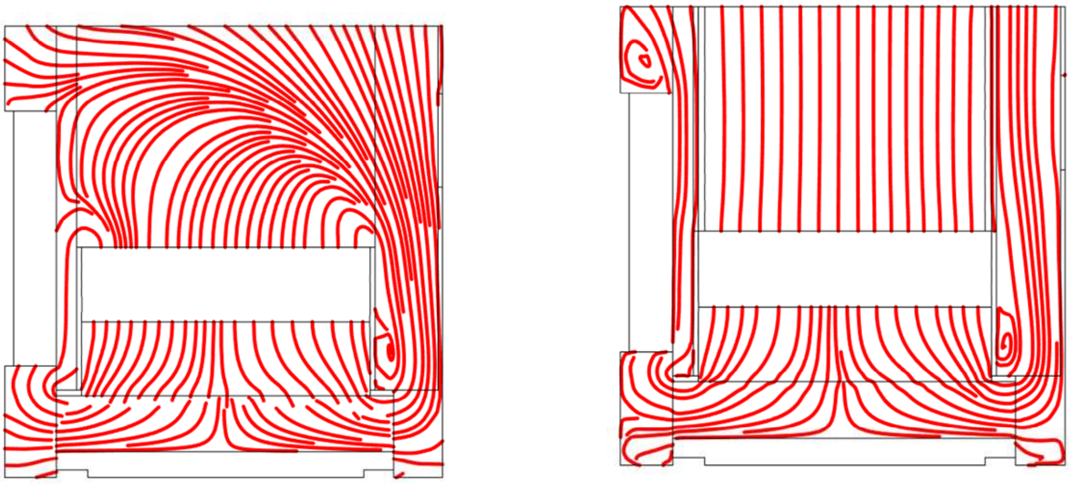


Fig. 10. Camera model divided into 2 smaller



Case A, n=24% Case B, n=100%

Fig. 11. Comparison of two air flow paths

CONCLUSIONS

1. CCD camera was designed and manufactured within the “Pi of the sky” project. Its thermal design allows to 10s exposure time. Thermal analyses were performed to identify possible areas of improvements.

2. Within spin-off project new camera is being designed. Based on previous generation cameras experiences, study of different thermal design was performed. It will be included in final design and should ensure long exposure time, which will increase accuracy of astronomical observations.

ACKONWLEDGMENTS

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