2nd International Conference

CONSOLFOOD 2018

Advances in Solar Thermal Food Processing

January 22nd to 24th, 2018 – Faro Portugal

Modeling and Testing of a Parabolic Solar Cooking System with Heat Storage for Indoor Cooking

22/01/2018

Ndiaga MBODJI and Ali Hajji

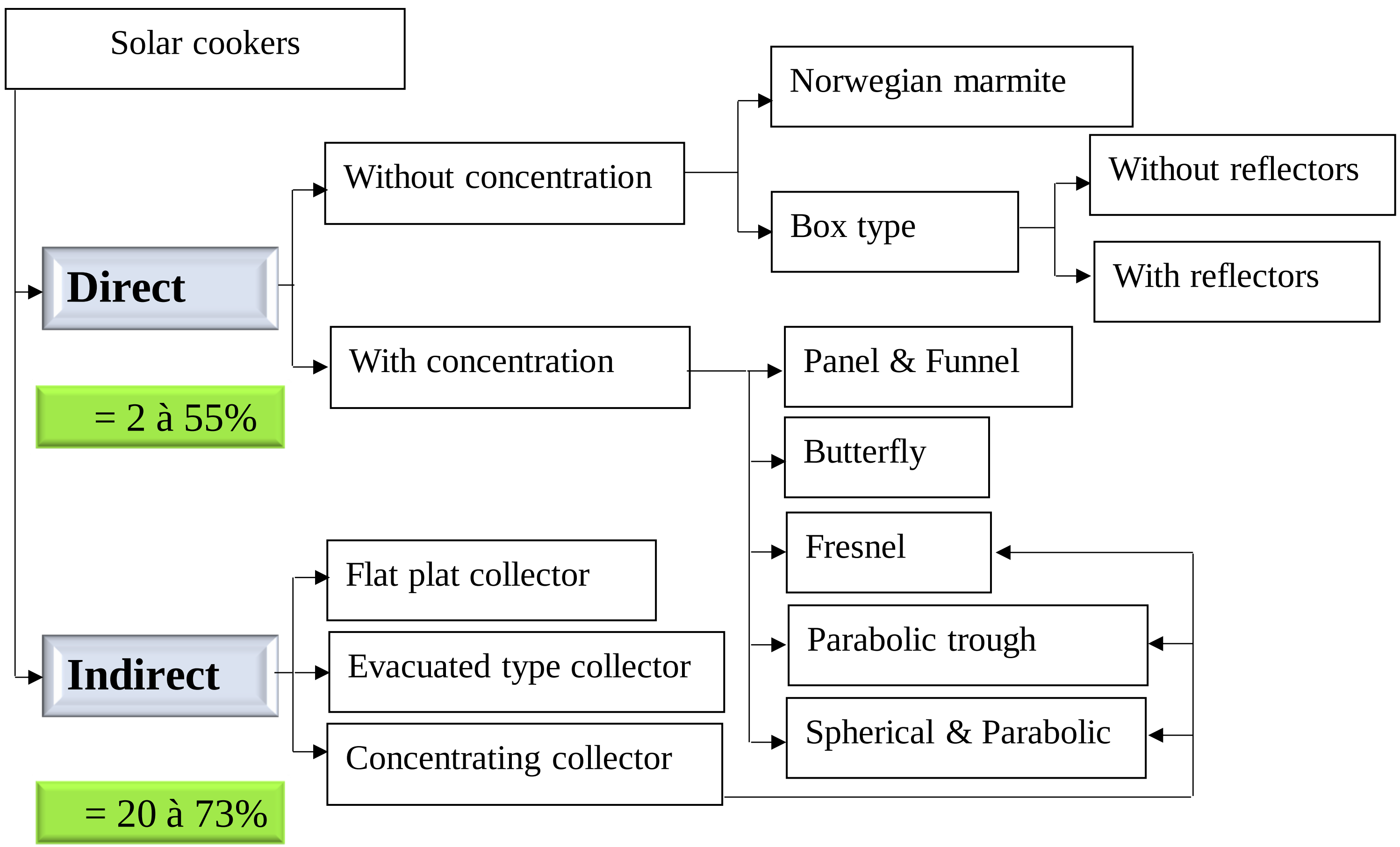
Process Engineering and Environment Research Unit
Institut Agronomique et Vétérinaire Hassan II

CONTENT

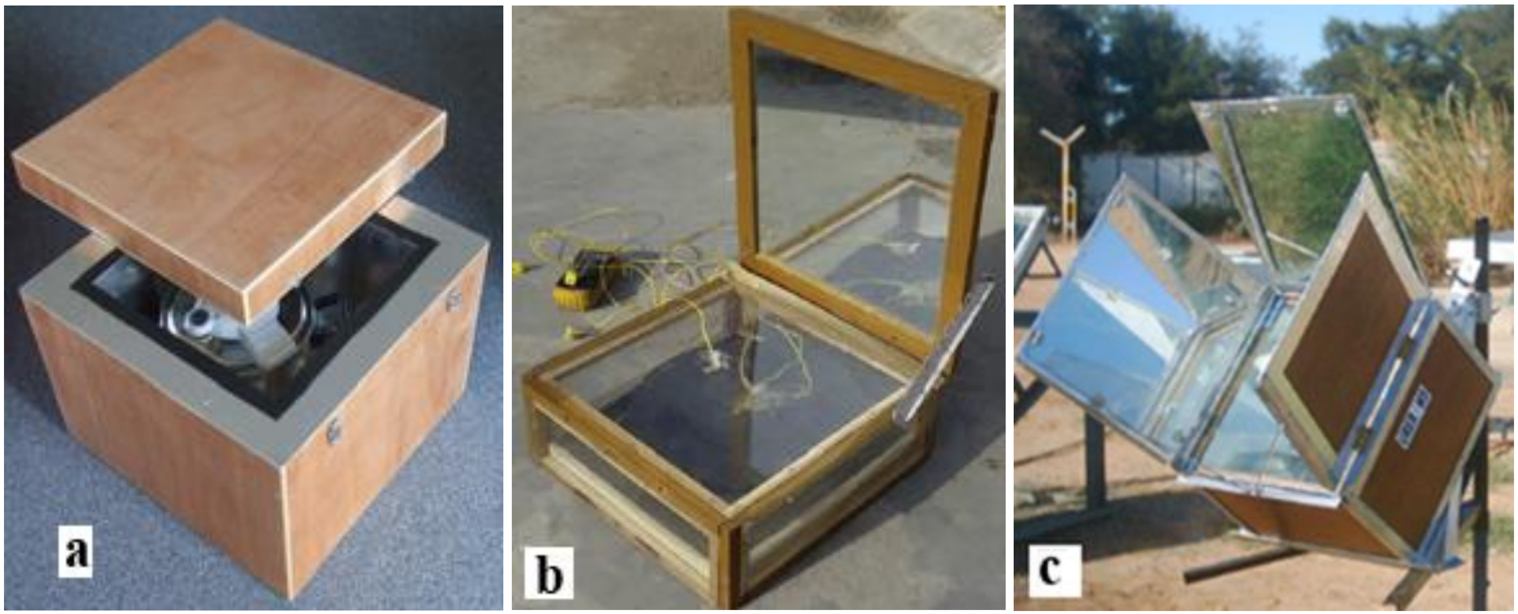
CONTENT

1. Introduction

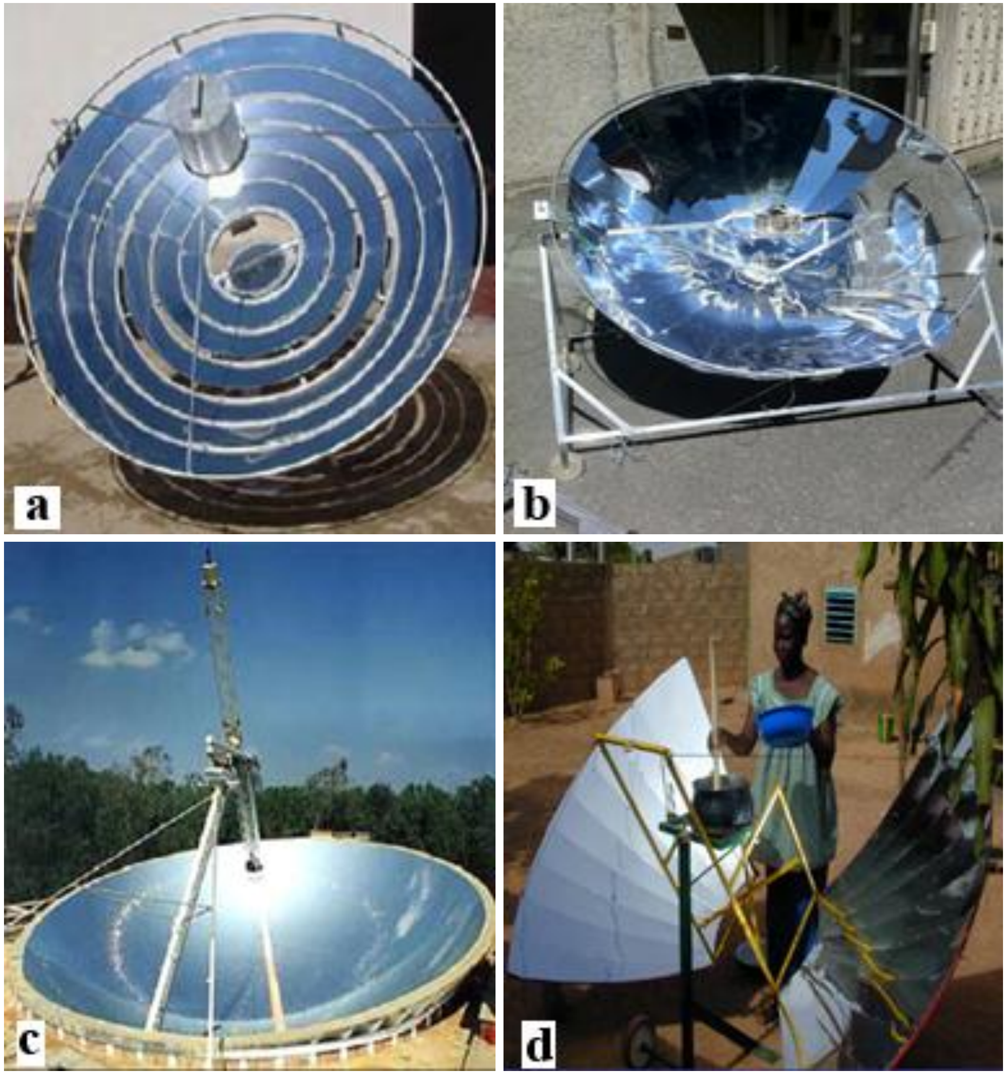
CLASSIFICATION OF SOLAR COOKERS



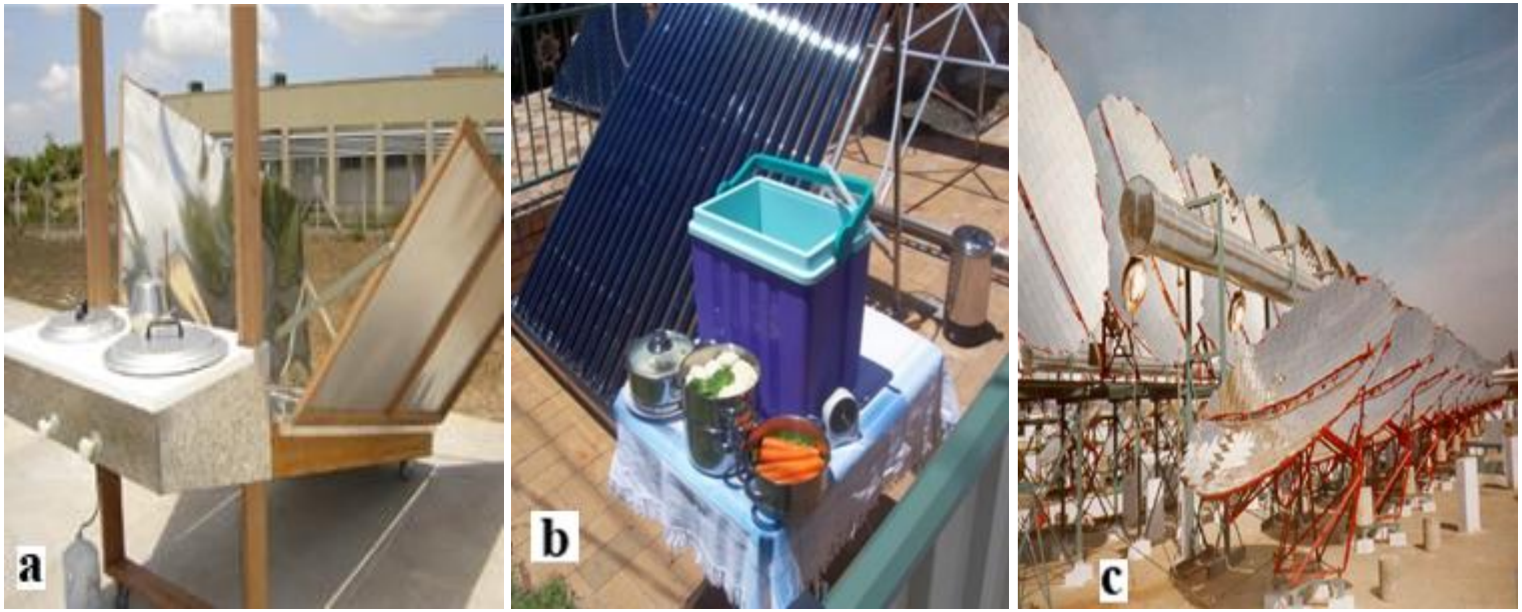
SOME PICTURES OF DIRECT SOLAR COOKERS



SOME PICTURES OF DIRECT SOLAR COOKERS



SOME PICTURES OF INDIRECT SOLAR COOKERS



STORAGE IN SOLAR COOKING

Sensible heat storage (variation of temperature)

Synthetic oil ;

Vegetable oil ;

Soil ;

Pebbles.

Latent heat storage (change of phase)

Acetamide ;

Acetanilide ;

Stearic acid ;

Erythritol ;

Salt hydrate Ba(OH)28H2O ;

Magnesium nitrate hexahydrate ;

PCM A-164.

IMPORTANCE OF MODELING

Modeling is a delicate step allowing to :

- Understand the links between physical quantities specific to the system;
- Predetermine the sizing of system components ;
- Perform simulations ;
- Improve design ;
- Analyze optical and thermal performance to increase their efficiency ;
- Optimize the operating conditions.

PROBLEMATIC

Introduction
Materiel and methods
Results and discussion
Conclusion

- Existence of several models for box and ovens types ;
- Little modeling work considered detailed dynamic temperature distribution and heat transfer in parabolic solar cookers systems with storage. (Prasanna, Mawire et al., Mussard) ;
- Existing models of parabolic solar systems - other than cooking applications - emphasize optimization of power production and not maximizing fluid temperature ;
- Maximum fluid temperature in the storage not only determines the types of food but also the cooking time.

OBJECTIFS

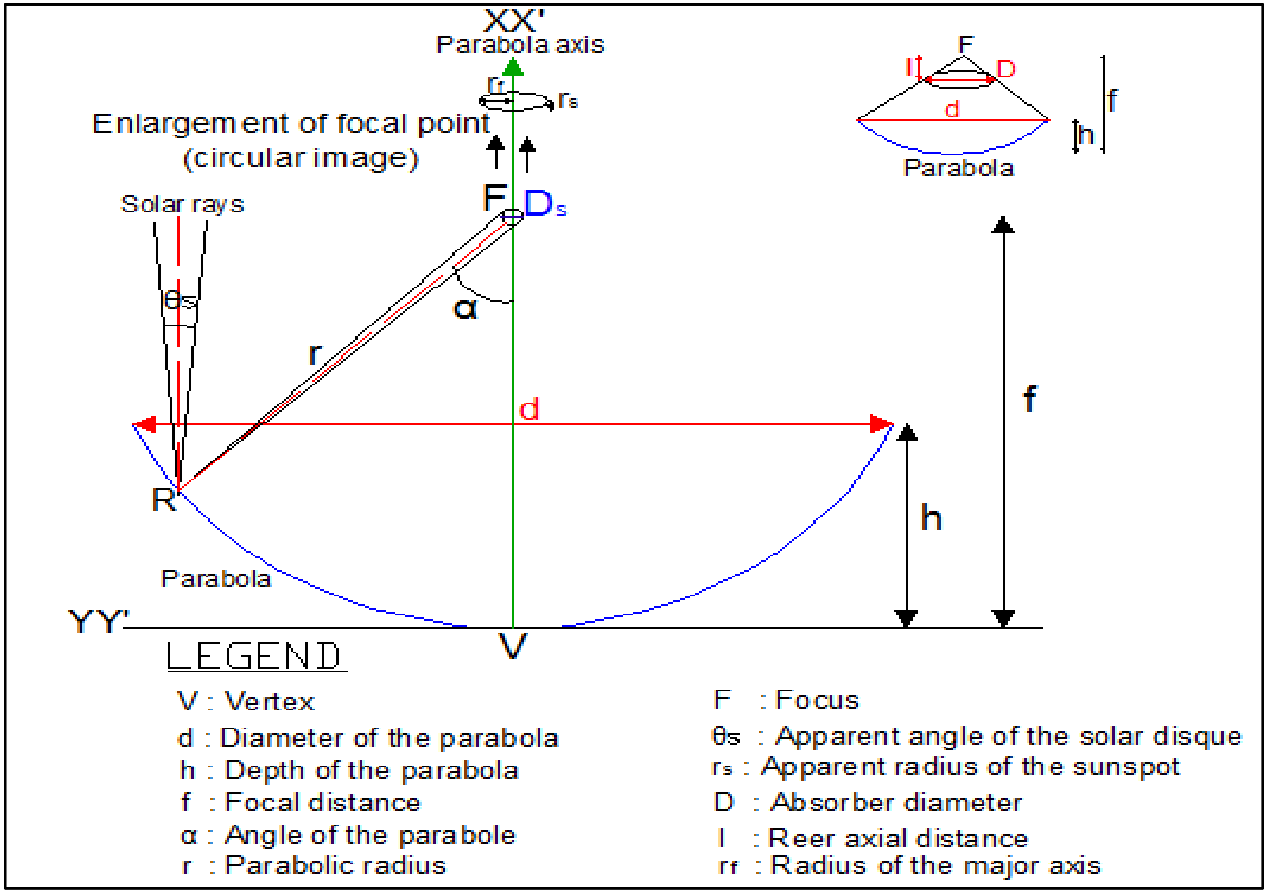
Model a parabolic solar system

Validate the simulation by experimental measurements

CONTENT

2. Materiel and methods

GEOMETRIC ELEMENTS



Geometric elements of the parabola

DESCRIPTION – FIRST EXPERIMENTAL DEVICE

System components

- **Concentrator** (**diameter 0.80 m and Depth de 0.08 m**) covered of **114 pieces of mirrors** of **5 x 5 cm** (**70% de la surface)** ;
- **Receiver (absorber)** composed of two black iron cylinders.
  - Inner cylinder with capacity of **1.57 L** (**diameter of 0.10 m and length of 0.20 m**) ;
  - Outer cylinder with a **diameter of 0.20 m** and a **length of 0.25 m** ;
  - **Glass wool** is placed between the two cylinders, as insulation ;
- **Tracking system** (sensitive mechanism based on photoelectric sensors and microcontroller) in two-axis with DC motors can withstand a load of **150 kg**.

DESCRIPTION – FIRST EXPERIMENTAL DEVICE

Geometric specifications

- Concentrator

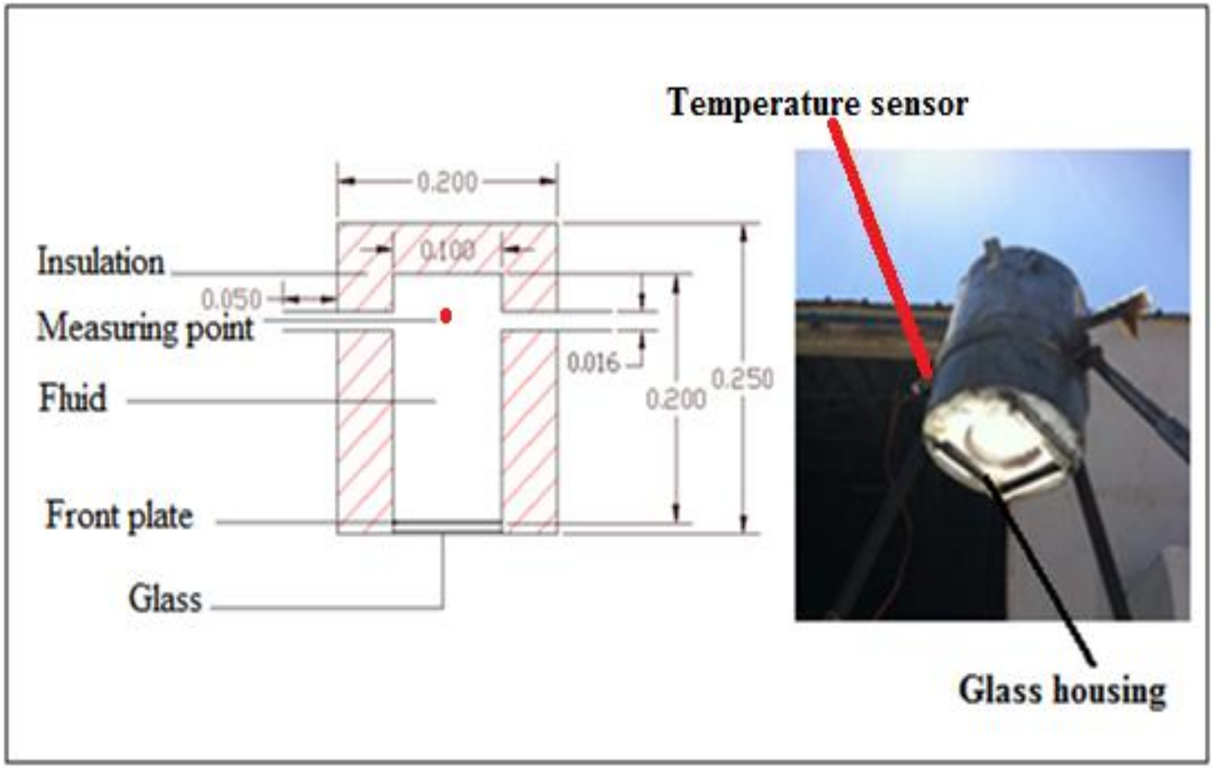
Diameter (m)	Depth (m)	Focal length (m)	Opening Angle (degré)	Concentrator Surface Area (m^2)	Arc length (m)
0.80	0.08	0.50	43.60	0.503	0.82

- Receiver

Diameter (m)	Length (m)	Surface capture (m^2)	Total area (m^2)	Sunspot radius (mm)	Concentration factor
0.10	0.20	0.008	0.079	3.7	45

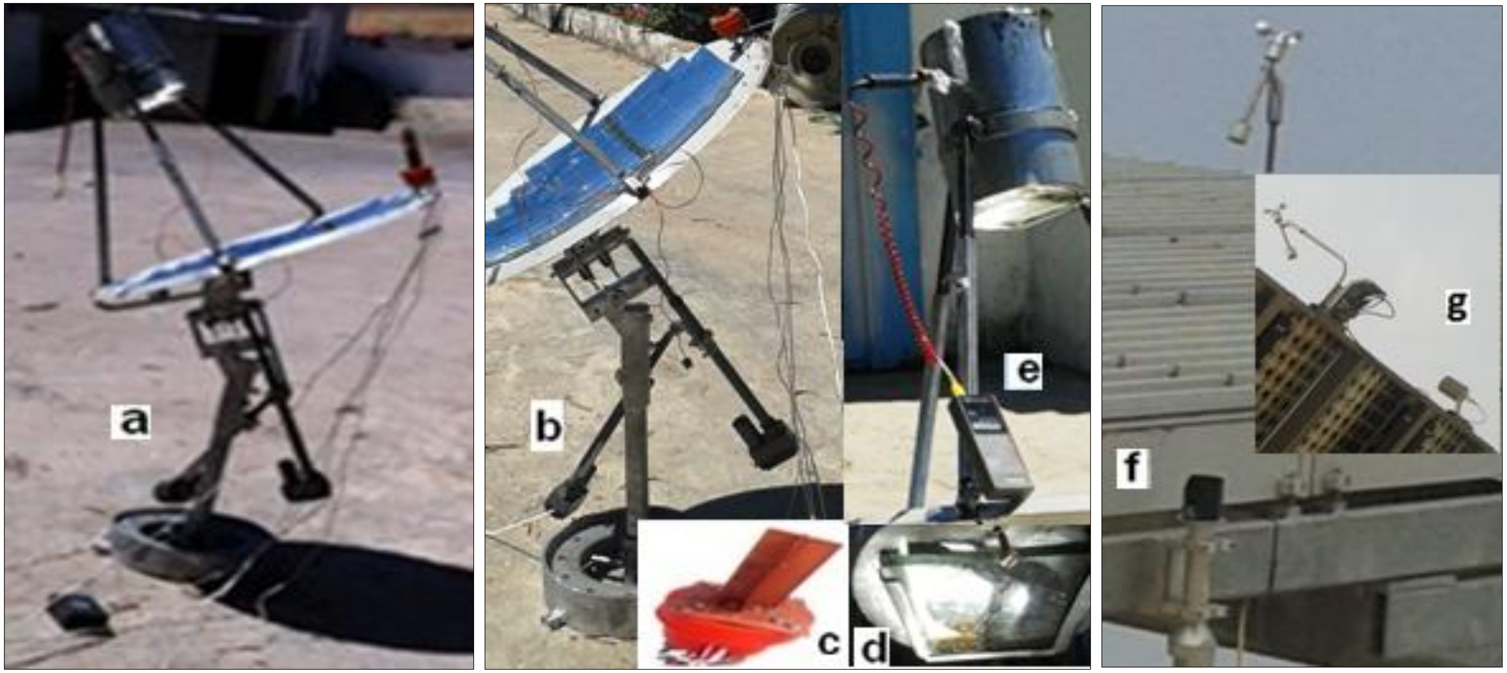
DESCRIPTION – FIRST EXPERIMENTAL DEVICE

Longitudinal section of the receiver



Longitudinal section and photograph of the absorber

PICTURES – FIRST EXPERIMENTAL DEVICE



Power = 0.15 kW

DESCRIPTION – SECOND EXPERIMENTAL DEVICE

System components

- **Concentrator** (**diameter 1.40 m and Depth de 0.16 m**) covered of **565 pieces of mirrors** of **5 x 5 cm** (**92% de la surface)** ;
- **Same receiver** ;
- **Storage tank** composed of two black iron cylinders;
  - Inner cylinder with capacity of **6.64 L** (**diameter of 0.12 m** and **length of 0.65 m**) ;
  - Outer cylinder with a **diameter of 0.24 m** and a **length of 0.77 m** ;
  - **Glass wool** is placed between the two cylinders, as insulation ;
- **Circulation pump** placed in the primary fluid circuit;
- **Numerical regulator** ;
- **Tuyauterie** in PER.

DESCRIPTION – SECOND EXPERIMENTAL DEVICE

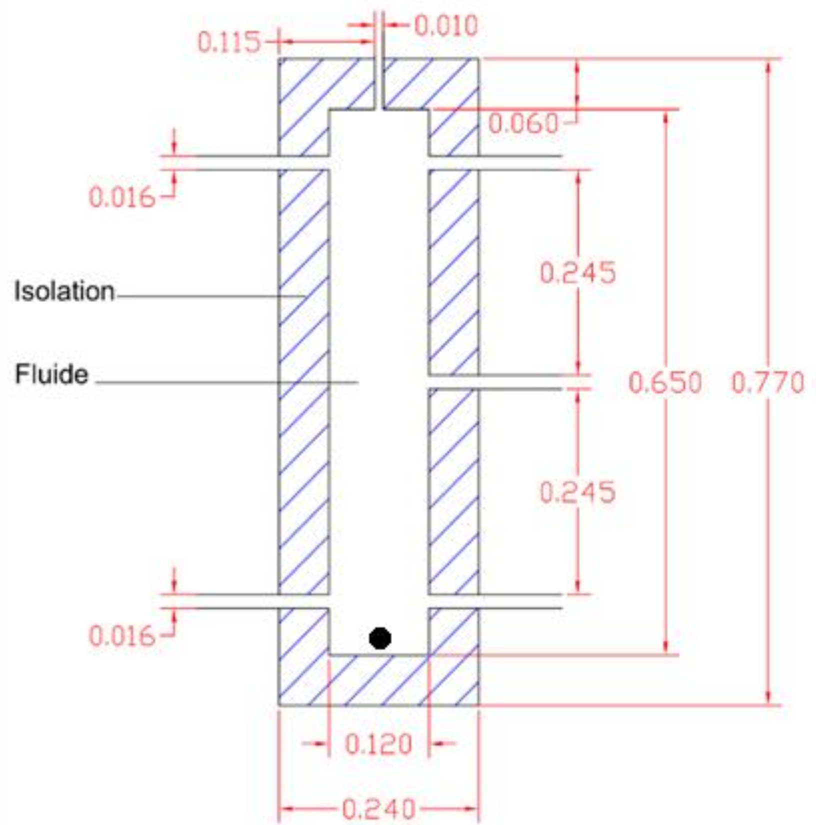
Introduction

Materiel and methods

Results and discussion

Conclusion

Longitudinal section of the storage



Longitudinal section and photograph of the storage

Geometric specifications

- Concentrator

Diameter (m)	Depth (m)	Focal length (m)	Opening Angle (degré)	Concentrator Surface Area (m^2)	Arc length (m)
1.40	0.16	0.77	49.13	1.540	1.64

- Receiver

Diameter (m)	Length (m)	Surface capture (m^2)	Total area (m^2)	Sunspot radius (mm)	Concentration factor
0.10	0.20	0.008	0.079	6.6	180

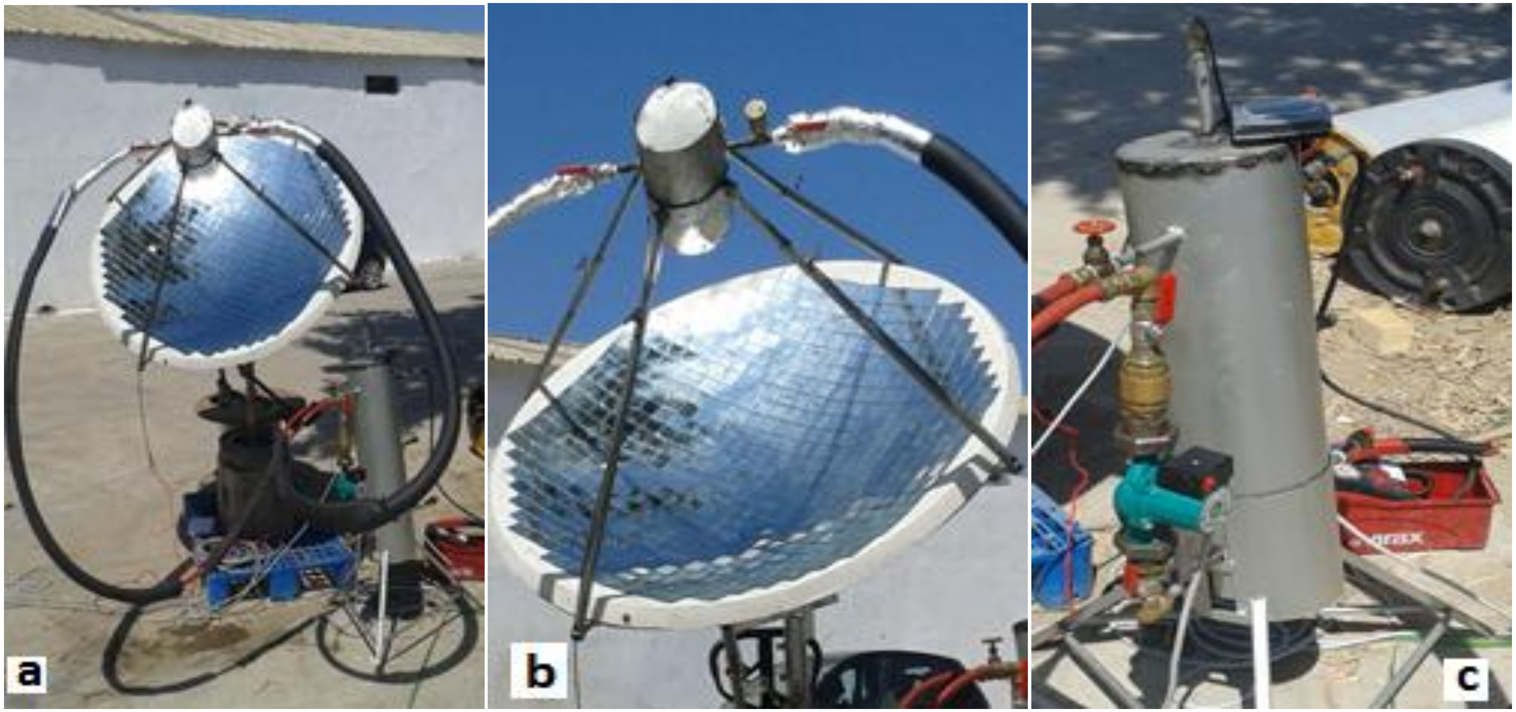
PICTURES – SECOND EXPERIMENTAL DEVICE

Introduction

Materiel and methods

Results and discussion

Conclusion



Power = 0.5 kW

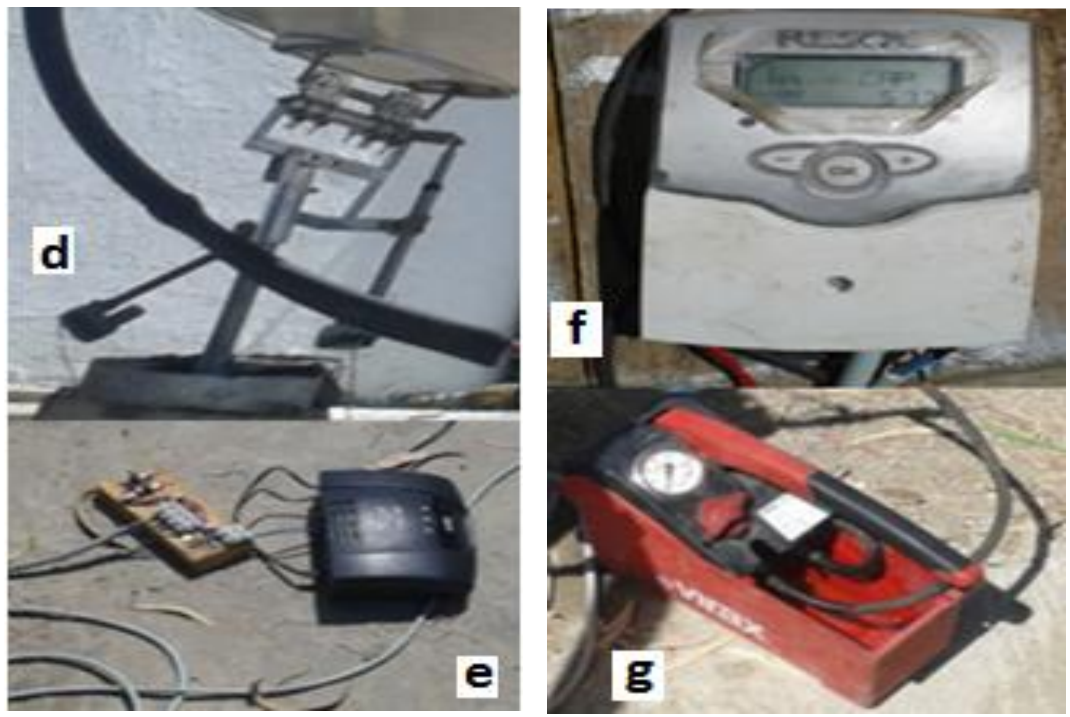
PICTURES – SECOND EXPERIMENTAL DEVICE

Introduction

Materiel and methods

Results and discussion

Conclusion



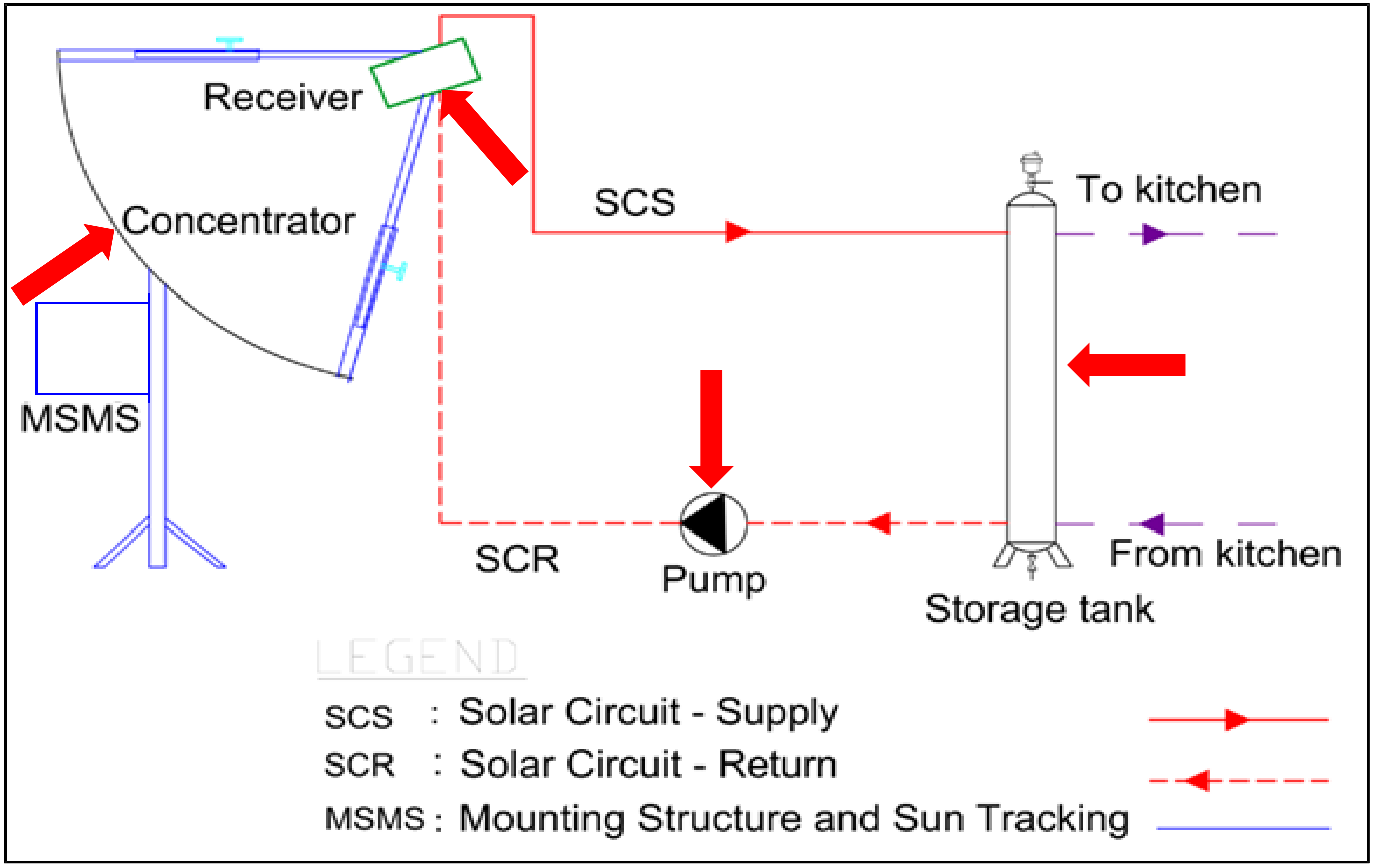
OPERATING PRINCIPLE

Introduction

Materiel and methods

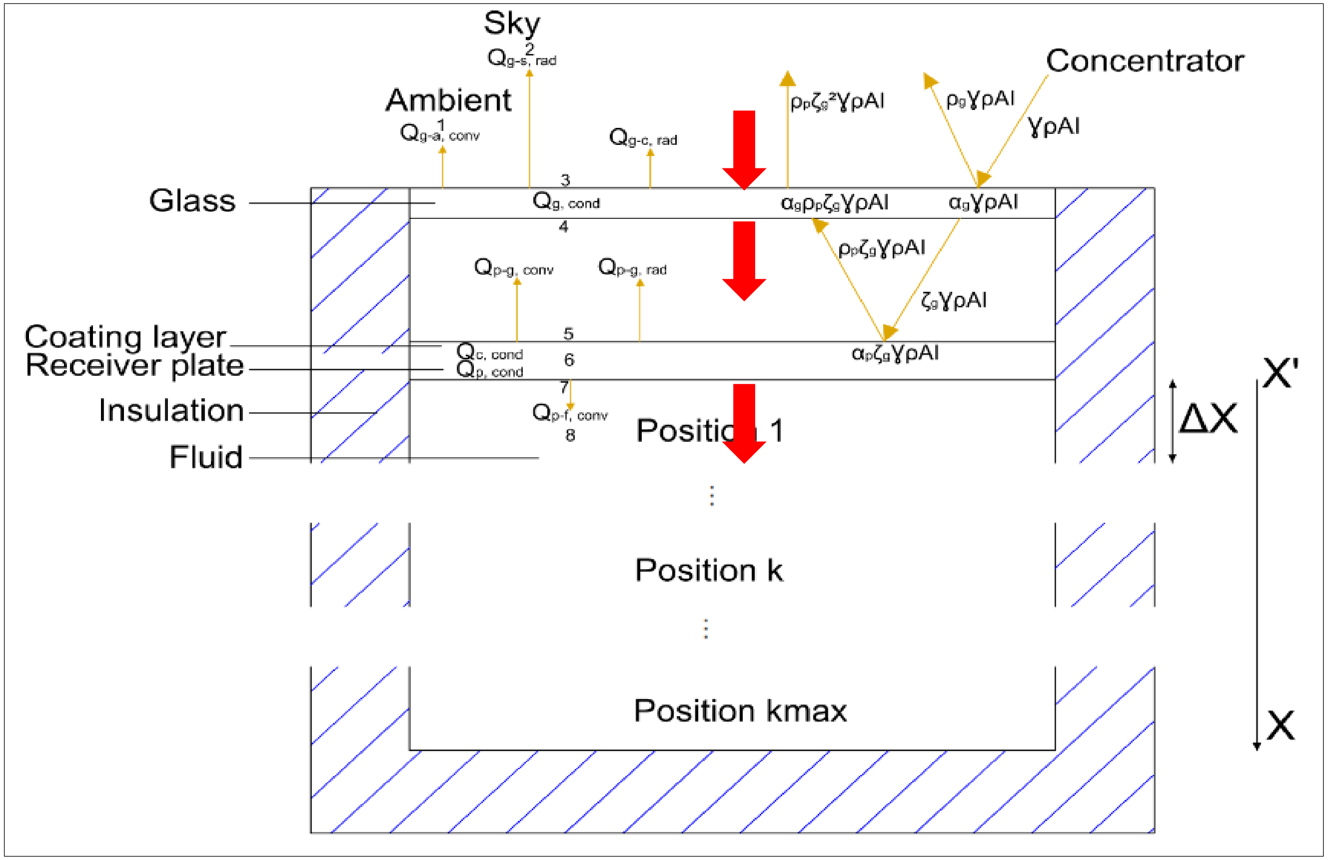
Results and discussion

Conclusion



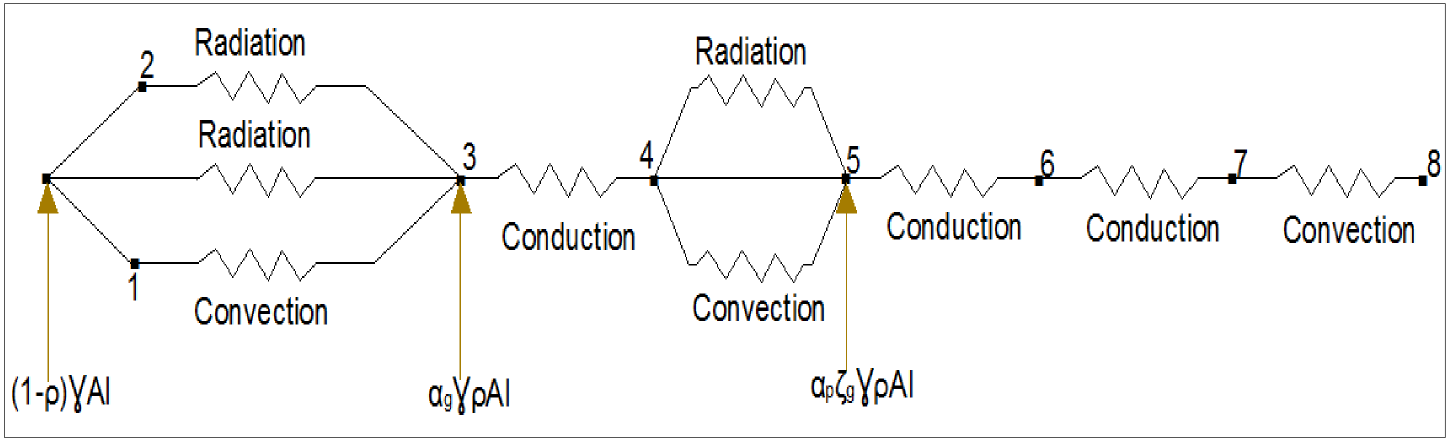
Schematics of a solar cooking system with heat storage

HEAT TRANSFER MODES



Cross section of the receiver with heat transfer processes

HEAT TRANSFER MODES



Equivalent thermal resistance model

CONTENT

Introduction

Materiel and methods

Results and discussion

Conclusion

3. Results and discussion

GOVERNING EQUATIONS AND NUMERICAL SOLUTION

- One-dimensional model based on energy balances ;
- Resolution with the explicit finite difference ;
- Hypothèses (incompressibility of the fluid and without change of phase, opacity of the glass cover with infra-red irradiations etc.) ;
- Application of the first law of thermodynamics between times t et t + Δt
- For receiver plate, the energy balance is given (from receiver to glass):

$$m_p C_p \Delta T_p = [\alpha_p \tau_g \gamma \rho A_c I_c - h_3 (T_p - T_{f,r}^1) A_p - (h_1 + h_2)(T_p - T_g) A_g] \Delta t \qquad (1)$$

GOVERNING EQUATIONS AND NUMERICAL SOLUTION

- Introduction
- Materiel and methods
- **Results and discussion**
- Conclusion

- Fluid portion in the position 1 of the receiver:

$$m_{r,k} C_f \Delta T_{f,r}^{1} = \left[\dot{m}\, C_f \left(T_{f,r}^{2} - T_{f,r}^{1}\right) + h_3\left(T_p - T_{f,r}^{1}\right) A_p - \frac{\lambda_f}{\Delta X_r}\left(T_{f,r}^{1} - T_{f,r}^{2}\right) A_p - h_g\left(T_{f,r}^{1} - T_a\right) S_{ur} \right] \Delta t \quad (2)$$

- Fluid portion in the intermediate position k of the receiver:

$$m_{r,k} C_f \Delta T_{f,r}^{k} = \left[\dot{m}\, C_f \left(T_{f,r}^{k+1} - T_{f,r}^{k}\right) + \frac{\lambda_f}{\Delta X_r}\left(T_{f,r}^{k-1} - T_{f,r}^{k}\right) A_p - \frac{\lambda_f}{\Delta X_r}\left(T_{f,r}^{k} - T_{f,r}^{k+1}\right) A_p - h_g\left(T_{f,r}^{k} - T_a\right) S_{ur} \right] \Delta t \quad (3)$$

- Fluid portion in the position kmax of the receiver:

$$m_{r,k} C_f \Delta T_{f,r}^{kmax} = \left[\dot{m}\, C_f \left(T_{f,s}^{1} - T_{f,r}^{kmax}\right) + \frac{\lambda_f}{\Delta X_r}\left(T_{f,r}^{kmax-1} - T_{f,r}^{kmax}\right) A_p - h_g\left(T_{f,r}^{kmax} - T_a\right)\left(S_{ur} + A_p\right) \right] \Delta t \quad (4)$$

GOVERNING EQUATIONS AND NUMERICAL SOLUTION

Introduction

Materiel and methods

Results and discussion

Conclusion

- Fluid in the position 1 of the storage tank:

$$m_{s,i} C_f \Delta T^{1}_{f,s} = \left[\dot{m}\, C_f \left(T^{2}_{f,s} - T^{1}_{f,s}\right) - \frac{\lambda_f}{\Delta X_s}\left(T^{2}_{f,s} - T^{1}_{f,s}\right) A_s - h'_g \left(T^{1}_{f,s} - T_a\right)\left(S_{us} + A_s\right) \right] \Delta t \qquad (5)$$

- Fluid in the position i of the storage tank:

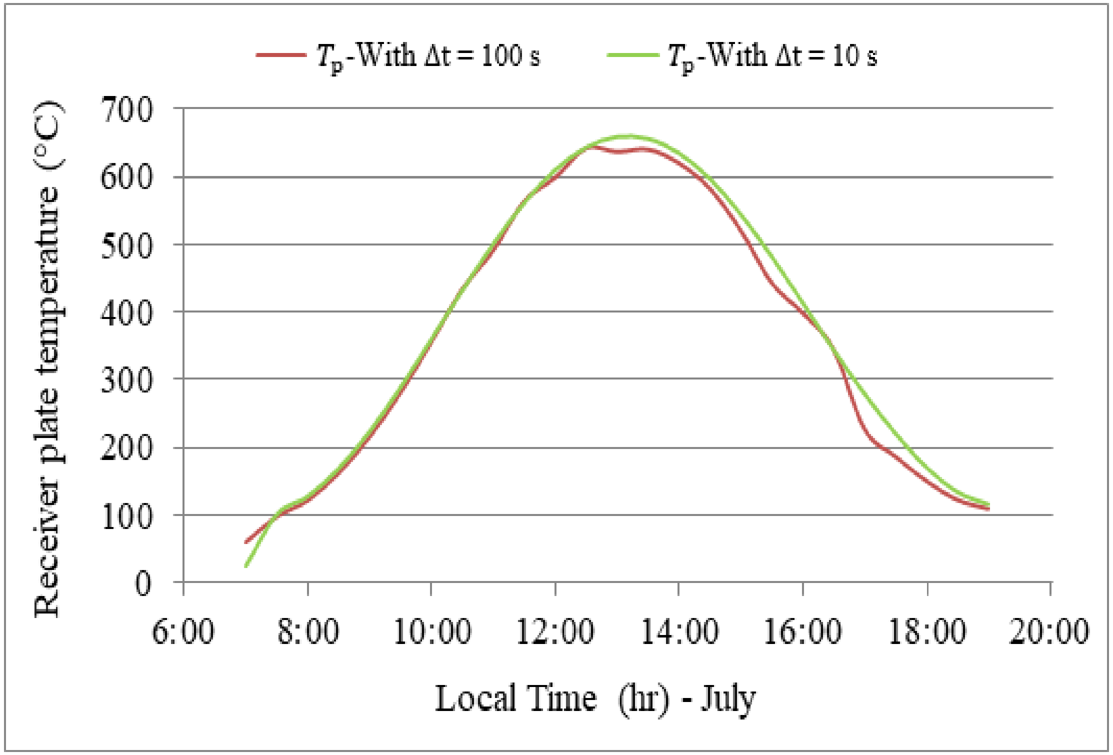
$$m_{s,i} C_f \Delta T^{i}_{f,s} = \left[\dot{m}\, C_f \left(T^{i+1}_{f,s} - T^{i}_{f,s}\right) + \frac{\lambda_f}{\Delta X_s}\left(T^{i+1}_{f,s} - T^{i}_{f,s}\right) A_s - \frac{\lambda_f}{\Delta X_s}\left(T^{i}_{f,s} - T^{i-1}_{f,s}\right) A_s - h'_g \left(T^{i}_{f,s} - T_a\right) S_{us} \right] \Delta t \qquad (6)$$

- Fluid in the position imax of the storage tank

$$m_{s,i} C_f \Delta T^{imax}_{f,s} = \left[\dot{m}\, C_f \left(T^{1}_{f,r} - T^{imax}_{f,s}\right) - \frac{\lambda_f}{\Delta X_s}\left(T^{imax}_{f,s} - T^{imax-1}_{f,s}\right) A_s - h'_g \left(T^{imax}_{f,s} - T_a\right)\left(S_{us} + A_s\right) \right] \Delta t \qquad (7)$$

CONVERGENCE AND VALIDATION OF THE NUMERICAL SOLUTION

Convergence at Δt = 0.1 s

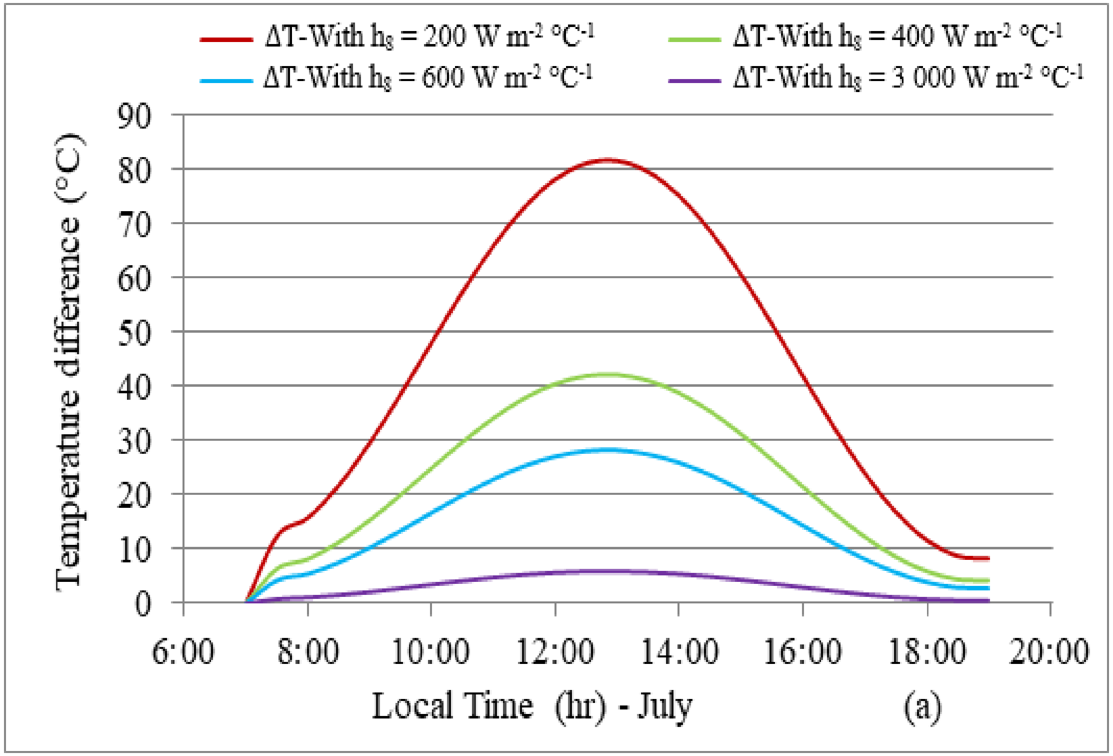


Time variation of the receiver plate temperature at different time steps

CONVERGENCE AND VALIDATION OF THE NUMERICAL SOLUTION

- Introduction
- Materiel and methods
- **Results and discussion**
- Conclusion

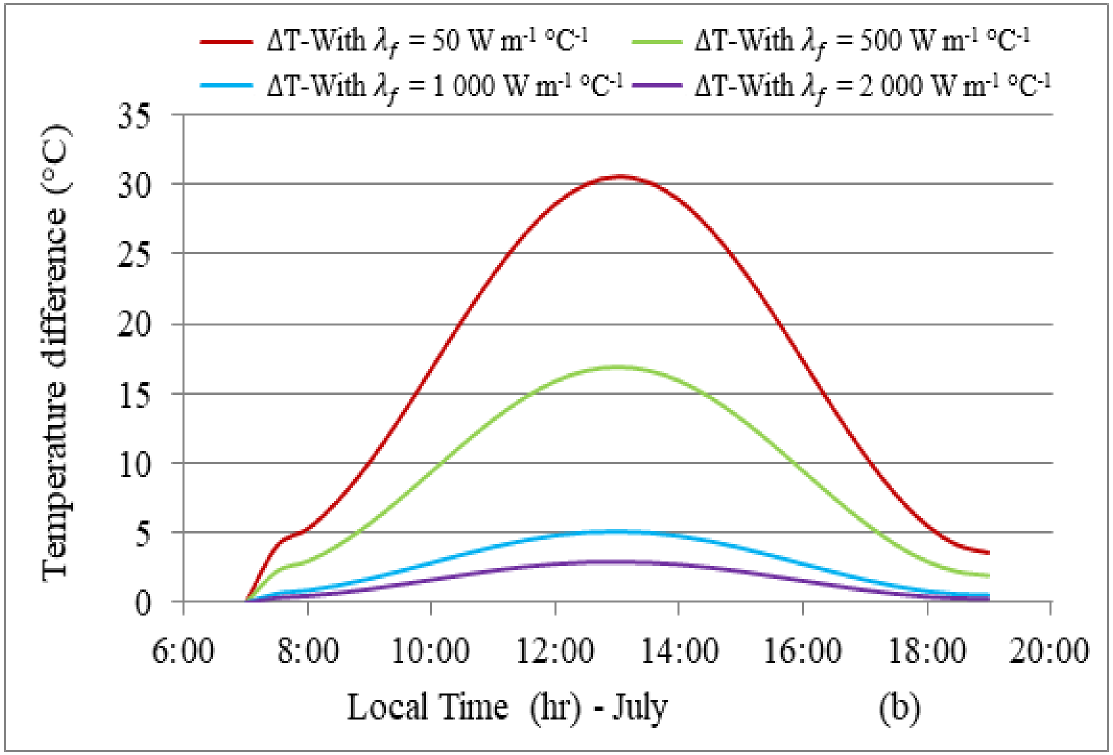
Convergence at $\Delta t = 0.1$ s



Time variation of the temperature difference between the plate and the fluid when increasing the heat transfer coefficient

CONVERGENCE AND VALIDATION OF THE NUMERICAL SOLUTION

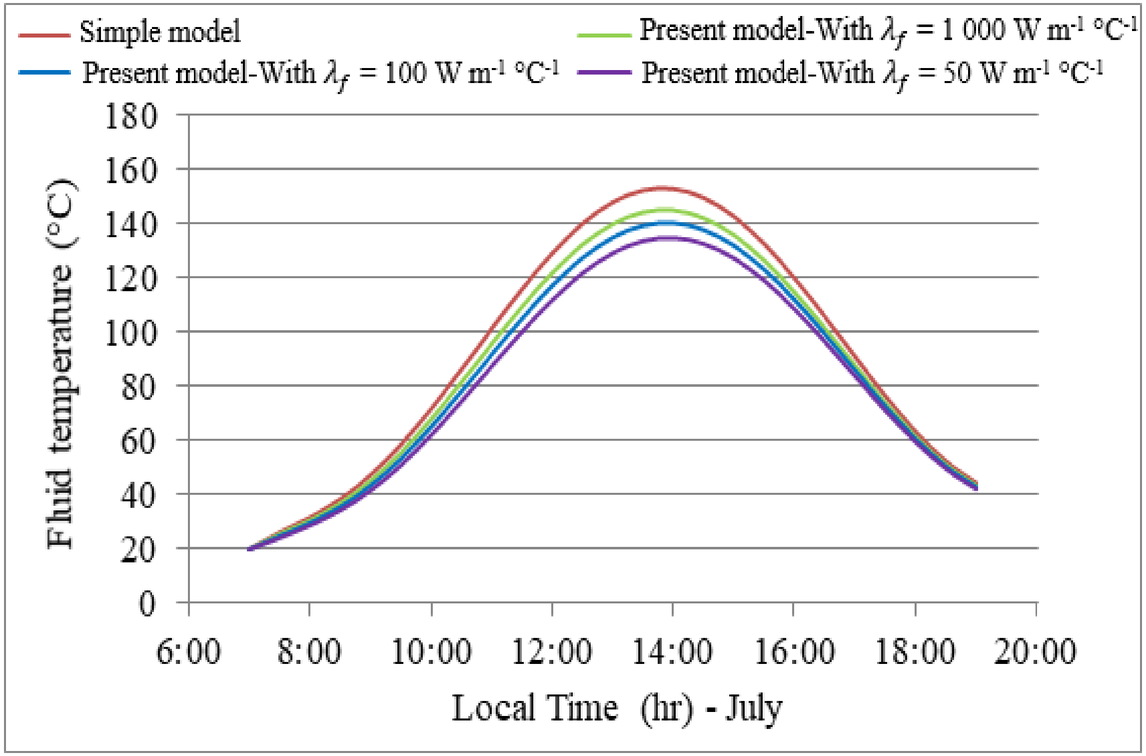
Convergence at Δt = 0.1 s



Time variation of the temperature difference between the plate and the fluid when increasing the fluid thermal conductivity

CONVERGENCE AND VALIDATION OF THE NUMERICAL SOLUTION

Convergence at $\Delta t = 0.1$ s



Comparison of the present model with the simple model

EXPERIMENTAL VALIDATION OF THE FIRST DEVICE

Introduction

Materiel and methods

Results and discussion

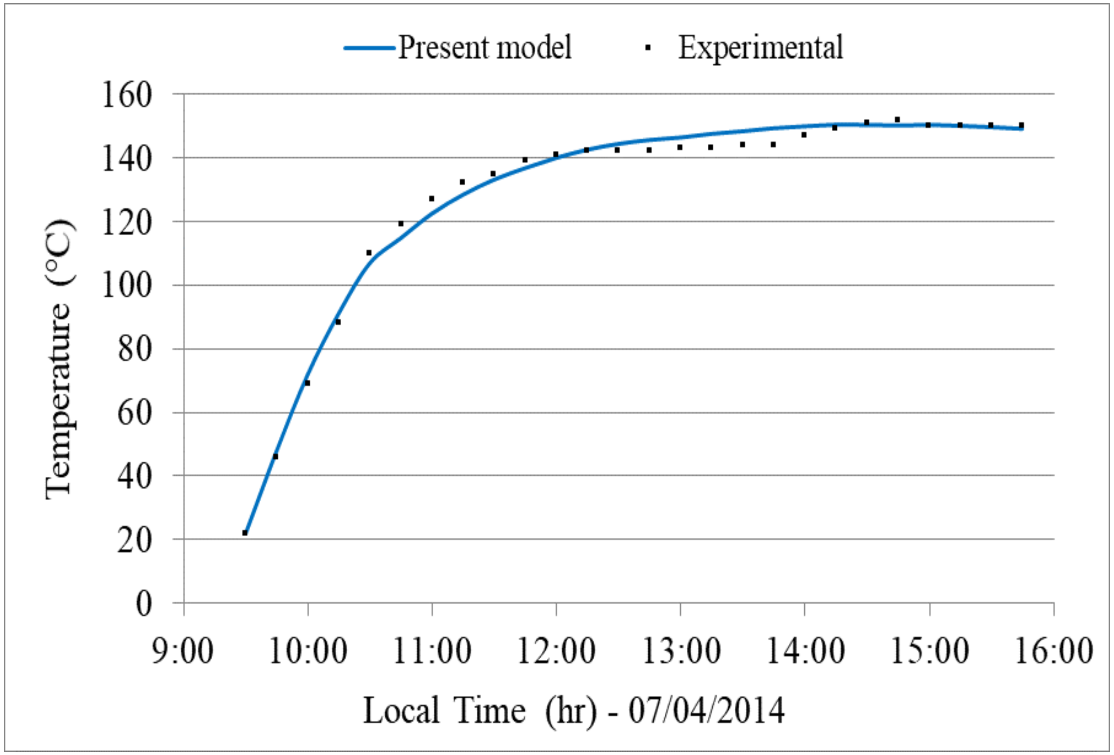
Conclusion

Aïn Atiq (Rabat)

33 53’ N, 6 59’ W

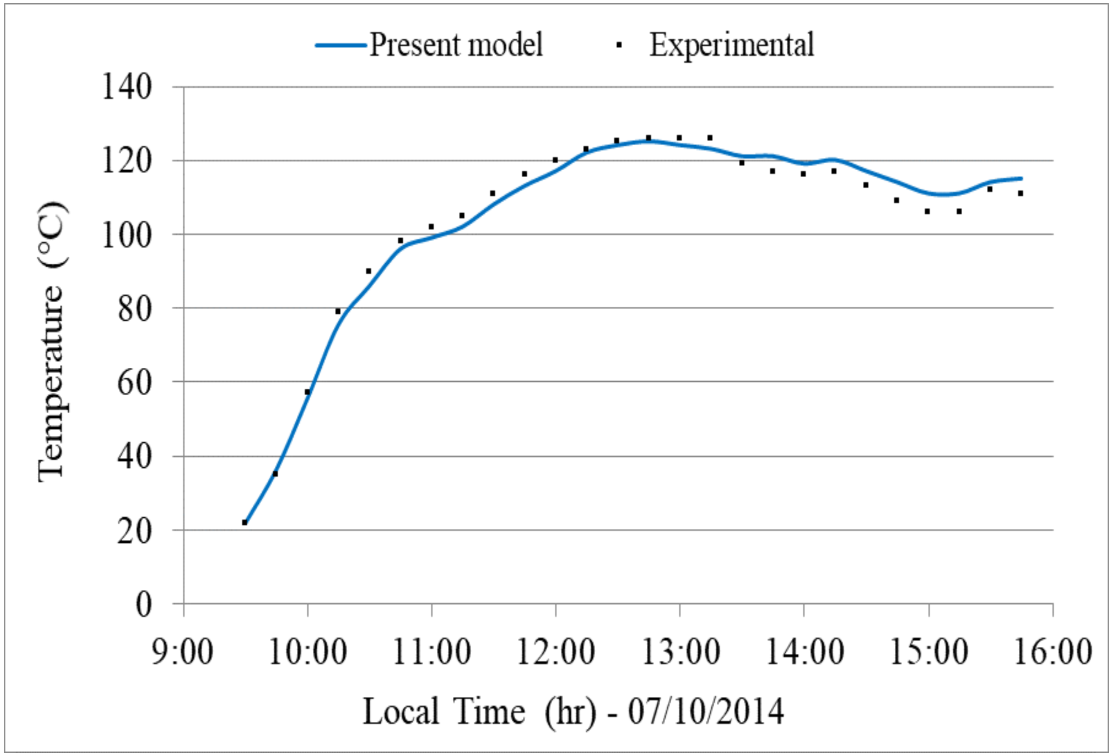
APRIL 24TH TO JULY 10TH, 2014

EXPERIMENTAL VALIDATION IN CLOSED CIRCUIT



Measured and predicted fluid temperature in the receiver in closed circuit of the first experimental device

EXPERIMENTAL VALIDATION IN CLOSED CIRCUIT



Measured and predicted fluid temperature in the receiver in closed circuit of the first experimental device

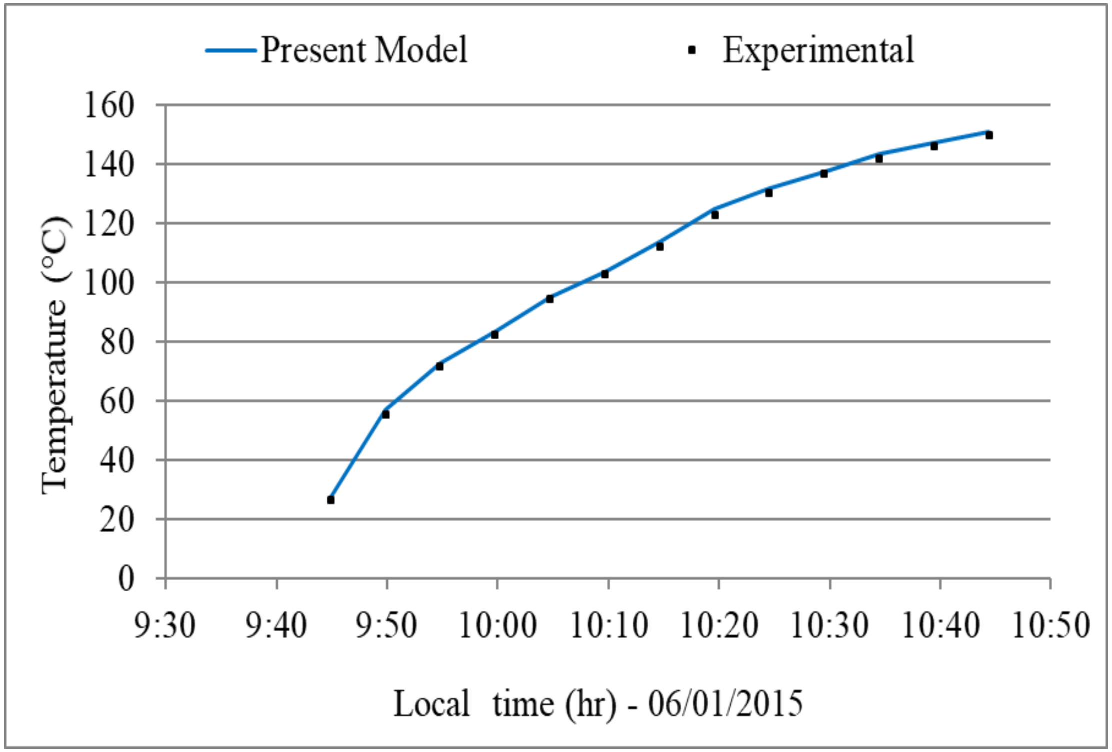
EXPERIMENTAL VALIDATION OF THE SECOND DEVICE

Aïn Atiq (Rabat)

33   53’ N, 6   59’ W

MAY 15TH TO JUNE 18TH, 2015

EXPERIMENTAL VALIDATION IN CLOSED CIRCUIT



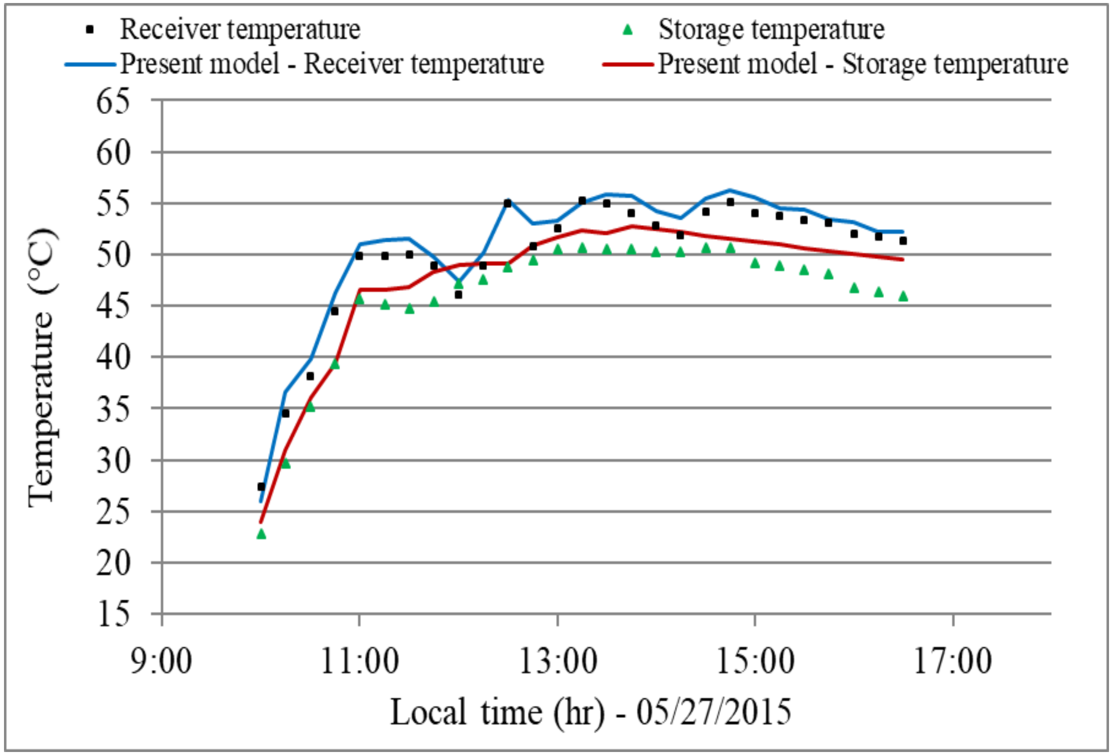
Measured and predicted fluid temperature in the receiver in closed circuit of the second experimental device

RELATIVE AND ROOT MEAN SQUARE ERRORS IN CLOSED CIRCUIT

Date	07/04/2014	07/10/2014	06/01/2015
RE (%) - Receiver	4.3	4.3	2.4
RMSE (C) - Receiver	2.8	3.0	1.2

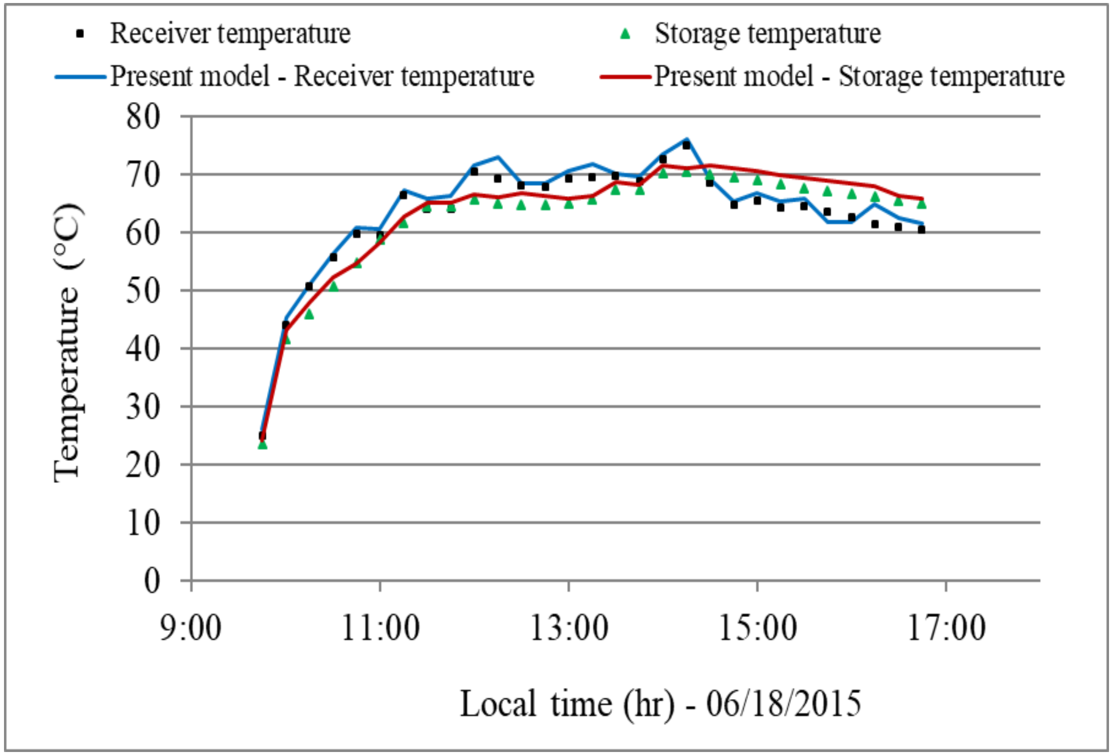
EXPERIMENTAL VALIDATION IN OPEN CIRCUIT

- Introduction
- Materiel and methods
- **Results and discussion**
- Conclusion



Measured and predicted fluid temperature in the receiver and in the storage tank in open circuit of the second experimental device

EXPERIMENTAL VALIDATION IN OPEN CIRCUIT



Measured and predicted fluid temperature in the receiver and in the storage tank in open circuit of the second experimental device

RELATIVE AND ROOT MEAN SQUARE ERRORS IN OPEN CIRCUIT

Date	05/27/2015	06/18/2015
ER (%) - Receiver	5.9	4.0
RMSE (C) - Receiver	1.3	1.5
ER (%) - Storage	7.5	4.4
RMSE (C) - Storage	1.9	1.3

CONTENT

4. Conclusion

CONCLUSION

Introduction

Materiel and methods

Results and discussion

Conclusion

- One-dimensional model solved by the explicit finite difference method ;
- Improvement over previous simple models with the current model including a non uniform temperature and temperature difference between the glass, receiver cover, and thermal fluid ;
- Correct prediction of thermal behavior with a relative error of 4.4% and a mean squared error of 3 C between simulation results and experimental measurements;
- Model can be used for simulation, design improvement, system performance prediction, and optimization of operating conditions;

CONCLUSION

- Introduction
- Materiel and methods
- Results and discussion
- **Conclusion**

- Model used to do parametric analysis :
  - Weather conditions (solar radiation, wind) ;
  - Materiel optical properties (reflectance, absorptance, emissivity) ;
  - System design parameters (aspect ratio, exposure ratio, rim angle, interception factor, insulation thickness) ;
  - Operating parameters (mass flow, glazing, air between the glass and the plate on the front of the receiver, tracking mechanism, nature of the fluid, heat losses).

Thank you for your attention