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DEVELOPMENT OF ELECTRO-MAGNETIC PUMP FOR THE ASTRID SODIUM-COOLED FAST REACTOR

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Abstract – In the framework of the SFR (Sodium Fast Reactor) prototype called ASTRID (Advance Sodium Technological Reactor for Industrial Demonstration), the large capacity Electro-Magnetic Pumps (EMP) as main circulating pumps on the intermediate sodium circuits is applied instead of mechanical pumps by CEA. The use of EMP has several decisive technological merits compared with mechanical pump in the reactor design, operation and maintenance. Nevertheless, some theoretical and technological developments have to be carried out in order to validate the design tools which take Magneto Hydro Dynamic (MHD) phenomena into account and the applicability of the EMP to the steady state and transient operating conditions of ASTRID. For their developments, a collaboration agreement between the CEA and TOSHIBA Corporation came into force to carry out a joint work program on the EMP for ASTRID design and development. CEA carried out the theoretical analysis, and the EMP experimental model is constructed by CEA to support these theoretical developments. This model consists of a middle-size annular EMP for the liquid metal sodium. The various testing program using this model has been started in 2016.And, TOSHIBA carried out the examination of design specification for ASTRID, an electromagnetic design, a structural design and various analyses. The structure design has been examined the placement of the sodium boundary and the withstand pressure, etc. And, if the thicknesses of the structure increase for withstand pressure, the pump efficiency falls because the loss of the electromagnetic force increases. Therefore the balance of withstand pressure and the efficiency has been considered by an electromagnetism design. This paper describes the design studies and experimental activities for the EMP development within the framework of the CEA-TOSHIBA collaborations.

I. INTRODUCTION

SFR is one of the 4th –generation Sodium-cooled fast reactor (GENIV) concepts selected to secure the nuclear fuel resources and to manage radioactive waste. In the June 2006, French Government submitted CEA to design studies of ASTRID prototype as a part of sustainable management of radioactive materials and wastes [1] in collaboration with industrial partners. ASTRID will be an industrial prototype with improving safety, operability and robustness against external hazards compared with previous SFRs for aim at a GENIV safety and operation.

The ASTRID pre-conceptual design is a sodium-cooled pool type reactor of 1500 MWth with intermediate circulation system and generating about 600 MWe. The target lifetime for ASTRID is 60 years. The pre-conceptual design phase has been focusing on innovation and technological breakthroughs, while maintaining risk at an acceptable level. This phase was conducted from 2010 to 2012 and investigated numerous open options. In these options, it has been decided to implement EMPs as the main circulation pumps on the intermediate circulation system. EMP has several advantages for the reactor design, operation and maintenance.

In the conceptual design phase to be next to the pre-conceptual design phase from 2013 to 2015, the ASTRID design was updated. Next phase for the basic design of ASTRID is undergoing during 2016 to 2019.
The most promising technology of EMP for the specific operating conditions of SFR is the Annular linear induction pump (ALIP). However, to confirm the applicability to ASTRID, some of theory and technology about EMP have to be validated by design tools which are based on MHD phenomena and can considered transient operating conditions.
A collaboration agreement for carrying out a joint work program on the ASTRID EMP design and development was concluded between CEA and TOSHIBA Corporation in April 2012. This paper describes the dedicated design studies and experimental activities for EMP development within the framework of this collaboration.

II. Application of EMP for ASTRID

The basic structure of the EMP is shown in FIG.1, and it consists of the duct made of double concentric cylinder tubes and the inner / outer stator. The iron cores are installed on the individual stators toward the radial direction. The ring coils covered by heat-resistant insulation are installed in the slots of these iron cores. And, the casing is installed around the coils and the iron cores. The voltage applied to these electromagnetic coils yields an induced current in the sodium. The sodium is driven by the interaction of the sliding magnetic field and the induced current. EMP which is applied to the intermediate circulation loop of SFR is possibility of giving the several potential merits about the SFR design and maintenance. These merits in particular are the followings;

- Merits of the simplified system
  EMP has the merit to make unnecessary the auxiliaries required for mechanical pump. These auxiliaries are dedicated for reduction gear, mechanical seals, lubricating oil system and pump over-flow system to cover sodium leakage on the rotating shaft.

- Merits of the circulation system
  EMP is able to be design without free surface level of sodium. Therefore, installing an EMP on the intermediate circulation loops would simplify the loop design itself. This would make it possible to reduce the piping length and sodium volume, resulting in a simplified intermediate circulation loop implementation.

- Merits of the maintenance
  EMP has several decisive technological merits compared with mechanical pump: no moving parts, no lubricant loop and reduced maintenance. The EMP maintenance time is estimated to be ten times lower than for mechanical pumps.

To fully benefit from the EMP merits, this component has to be self-cooled, which means it has no auxiliary cooling system.

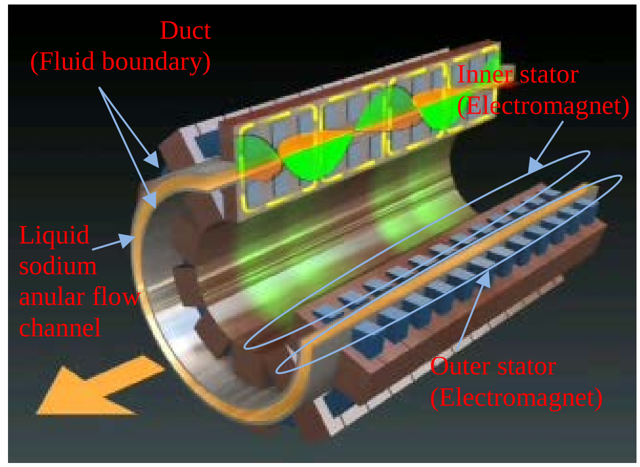

FIG.1. Basic structures of the LEMP

III. ASTRID EMP design specification

(1) Nominal operation

In the ASTRID reference reactor layout, there are four intermediate sodium loops with Intermediate Heat exchanger (IHX) and Sodium-Gas Heat Exchanger (SGHE) for the power conversion system. SGHE is considered for adoption in substitution for a conventional steam generator (SG) to eliminate the sodium water reaction. Each intermediate circulation loop integrates one EMP. They are located on the cold legs of the intermediate circulation loops (see FIG.2).
EMP design requirements for nominal operation conditions are shown in Table.1.
With the choice of SGHE, the pressure loss of the secondary loop increases and consequently the pump head of the EMP.

Table.1: EMP design requirements

Item	Value
Flow rate	1.98 m3/s
Pump head	0.5 MPa
Sodium temperature	
- Nominal operation	345°C
- Maximum at the thermal transient	540°C
Nominal design pressure	1.2 MPa

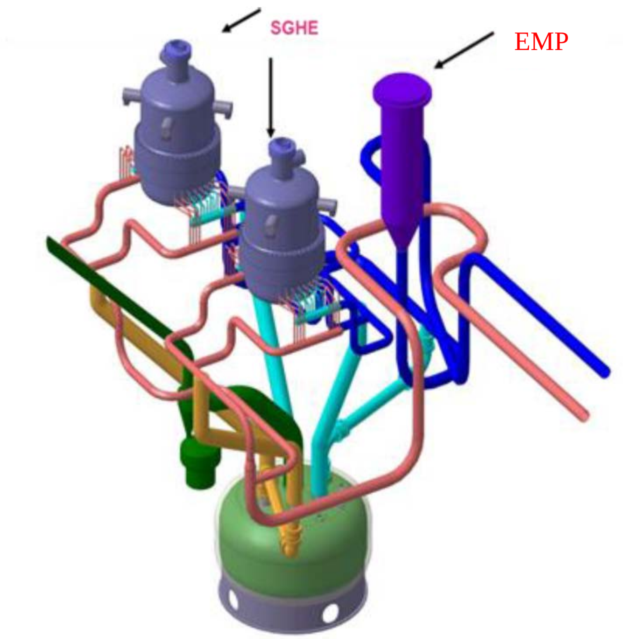

FIG.2. Example of a compact intermediate circulation loop with an EMP on the cold leg

(2)Thermal transient conditions

The thermal transient condition with a SGHE is still examining. Therefore, the most severe thermal transient condition for the EMP was assumed the loss of SG feed water. In this case, the automatic Reactor Shut Down occurs when the sodium temperature reaches 380°C at the SG outlet. At the same time, the intermediate sodium flow rate is reduced to 15 % of the nominal flow rate in 9 seconds. The sodium temperature at the SGHE outlet is then increased up to 540°C in 200 seconds and generates of a hot shock in cold leg of the intermediate circulation loop (see FIG.3). This type of transient is expected to occur 150 times during the reactor's 60-year lifetime.

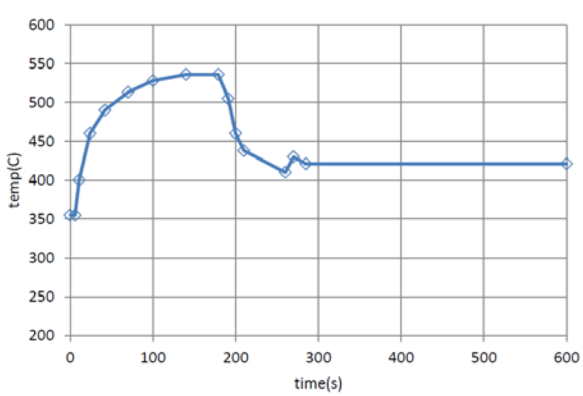

FIG.3. Thermal transient in case of hot shock in intermediate circulation loop

IV. ASTRID EMP design

(a) Electromagnetic design

Electromagnetic design is performed to satisfy the requirement for the pump head and the flow rate. The design parameters are the current, voltage, frequency, size of the coil and the iron core, the duct (fluid boundary) thickness, material of the duct,...etc. Especially, the duct thickness and material influences the pump efficiency. Pump efficiency is the ratio between the input power and the output power, and the duct creates loss by an eddy current. For this reason, the objective is to make duct thickness as thin as possible. On the other hand, the duct needs to satisfy the fluid pressure especially under external pressure. Furthermore, if the electrical resistivity of the duct material is small, the loss increases because of the eddy current that occurs in the duct. Therefore, we investigated the relationship between the duct material, the duct thickness and the efficiency.

Inner duct materials compared are SS304, SS316 and Inconel600. SS materials have physical property value for design in ASME code, and Inconel 600 was chosen as a typical nickel alloy. The biggest allowable stress is for Inconel600, then for SS316 and finally for SS304. The electrical resistivity is also big in same order.

The result is shown in FIG.4. This figure assumes outer duct SS304 of thickness 10mm and shows duct thickness and relationship of the pump efficiency when inside duct materials were changed. The duct thickness is 15mm in SS316, 20mm in SS304 and pump efficiency better with SS304 compared with SS316. This is because there are many eddy current losses by a duct thickness of SS304 being more large. In addition, SS316 has the electrical resistivity that is slightly bigger than SS304.

In the case of using Inconel600 as duct materials, pump efficiency and duct thickness is the best because of the larger proof stress and electrical resistivity. But, since main piping of ASTRID is SS316-based material, Inconel600 uses induce joint difficulties and complicates maintenance since it becomes an inspection item of the periodic inspection .Therefore, the duct material retained is SS316.

The examination result of an electromagnetic design in case of SS316 duct is shown in Table.2. Pump efficiency is about 40%. Almost 60% of the losses become heat, and most of that is released into the sodium and is use to heat the sodium. Among all losses, the loss induced by the duct was 24%. The other losses are the coil loss, the iron loss and the fluid loss. Therefore, the material selection and the thickness of the setting of the duct have a great influence on the pump efficiency.

A preliminary design of the stator of EMP is shown in FIG. 5.

Table.2: Main preliminary specification of the EMP

Item	Specification
Type	ALIP / Double stator
Terminal current	1913A
Terminal voltage	1780V
Capacity	5898KVA
Input power	2977kW
Frequency	18.3Hz
Number of poles	16
Sodium flow channel height	65mm
Inside diameter of the outer duct	1030mm
Out diameter of the inner duct	900mm
Stator length	5200mm
Efficiency	36%

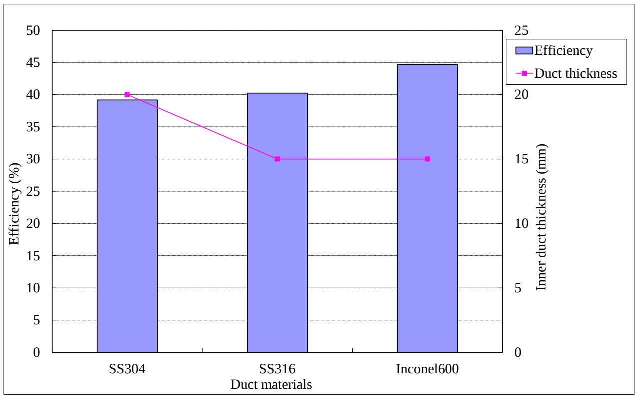

FIG.4. Compare result of the duct materials (Draft)

(b) Electromagnetic fluid analysis

To design the EMP, TOSHIBA performed an electromagnetic fluid analysis to define the pumping function and the electromagnetic characteristics. This analysis uses a code developed by TOSHIBA. This code solves coupled equations of the electromagnetism (Maxwell's equations) and the fluid dynamics (Navier-Stokes equation) in a two-dimensional axis model. By this analysis, the P-Q (pump head vs. flow rate) characteristic, the electromagnetic force distributions are calculated.

The axis-symmetrical analysis model takes into consideration the sodium channel, the concentric sodium channel duct, the inner and outer iron cores, the coils and the casing (see FIG.6). The number of meshes was made into about 100 meshes in the radial direction, and about 400 meshes in the axial direction for a total of 40000 meshes.

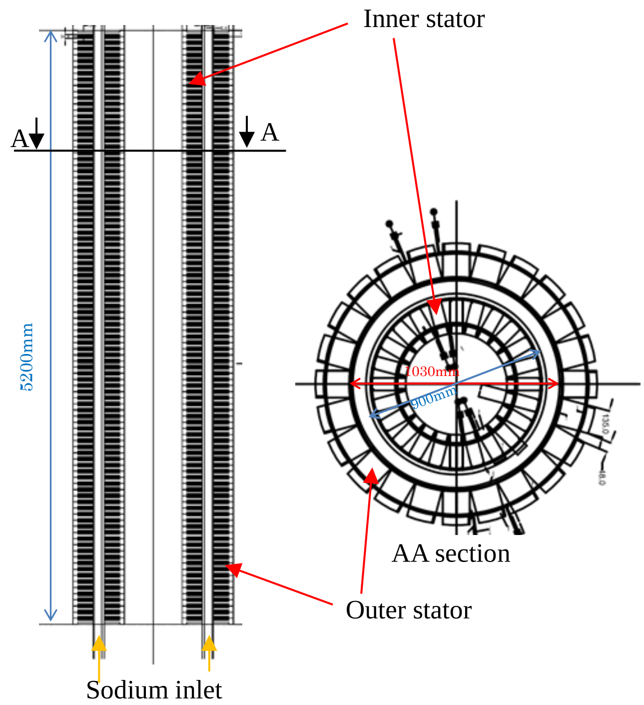

FIG.5. Main geometrical dimensions of stator of the EMP

Analysis conditions were 345°C for nominal sodium temperature and evaluates the flow, the developed pressure characteristic and the electromagnetic forces with a constant V/f ratio.

The P-Q characteristics are shown FIG.7. The ratio of voltage to frequency was set constant as analysis conditions. The pressure reached at the nominal flow rate of 1.98 m^3/s fully satisfied the specified 0.5 MPa in a stable control of flow area.

The analysis result of the electromagnetic-force distribution in an annular sodium channel is shown FIG.8. Although the negative thrust near 0.4 m and 4.7m in the axial direction is based on the end effect of the stator, this negative thrust (area) is smaller than the electromagnetic force of the stator. Therefore, it is thought that the fall of the pump performance by the end effect is small. And, almost electromagnetic force is committed to the axial direction used as developed pressure power, and there was almost no invalid electromagnetic-force to the developed pressure of the radial direction.

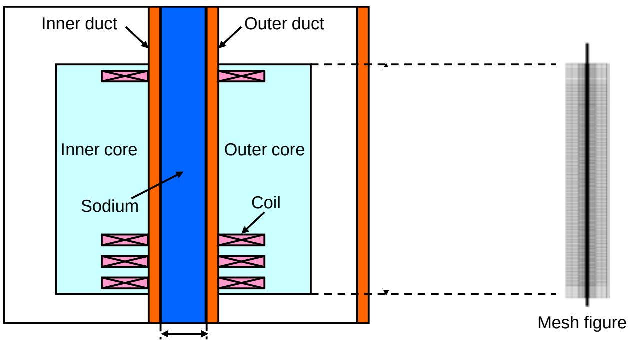

FIG.6. Analysis model of the 2D electromagnetic fluid analysis

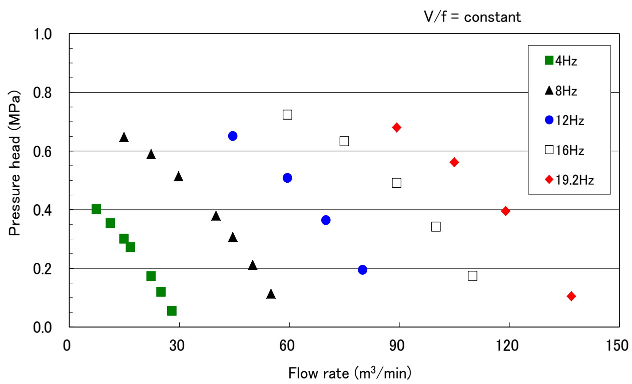

FIG.7. P-Q characteristic (Draft)

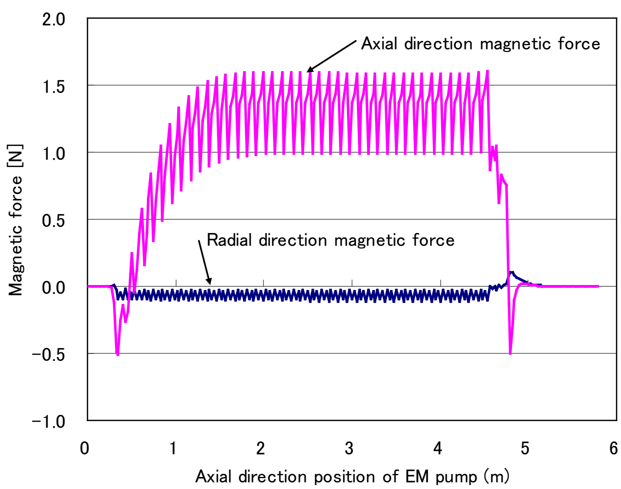

FIG.8. Magnetic force distribution (Draft)

(c) Structure design

It is necessary to determine the conceptual structure of EMP with consideration of the following. In addition, the structure of a stator part is fundamentally common.

- Bellows
  The bellows are required in order to absorb the thermal expansion difference of the portion which contacts sodium directly, and the portion which does not contact. Especially, in the case of a thermal transient, the thermal expansion difference becomes larger. In ASTRID, it is not allowed to implement bellows on sodium boundary. Therefore, a bellows must be installed in non-sodium boundary.
- Load transmission
  On EMP, the inner and outer stators are the heaviest parts. It is desirable to be the structure that such a load is supported at plural points.
- Position of the outlet nozzle
  As for an outlet nozzle position, it is desirable to shorten the secondary circuit piping and its' distance from a ceiling or a floor extension in interfaces with the civil engineering.
- Support structure
  Support structure has a type hung by a support cylinder inserted in a ceiling slab. If aseismic and thermal expansion are taken into consideration, hanging type is advantageous.

We examined structure to satisfy the demand mentioned above. A concept of structure of EMP is shown in FIG.9. In this structure, sodium flows in the duct from an inlet nozzle and is pressurized by receiving electromagnetic forces. And, sodium flows outside from an outlet nozzle of one place in the circumferential direction through a cylinder type plenum (upper plenum) at the duct outlet.
In this type, because a difference in temperature occurs between an outer duct and an outside casing at the time of thermal transient, a bellows is required. In addition, the bellows is necessary to set the non-sodium place. Therefore, the place of a bellows has been arranged on the outside casing for maintenance consideration. This solution advantageous because, the load transmission can be divide between the load of the outer stator and the inner stator and can this is possible to hang it from the upper flange. Support structure is the hanging type.
Since an outlet nozzle becomes close to ceiling slab, it is necessary to keep one's distance from a ceiling, and the full length of EMP becomes long. Gas plenum and sodium surface is unnecessary in this type. However, the gas vent line at the time of sodium filling is required. Moreover, because this type was the structure of receiving a thin duct for the load from the inlet piping, it has been improved by the structure which distributes piping load by adding a shroud to the outside of a casing. For the outlet nozzle through the casing, the penetration hole is larger than the

diameter of the outlet nozzle for consideration of thermal displacement.

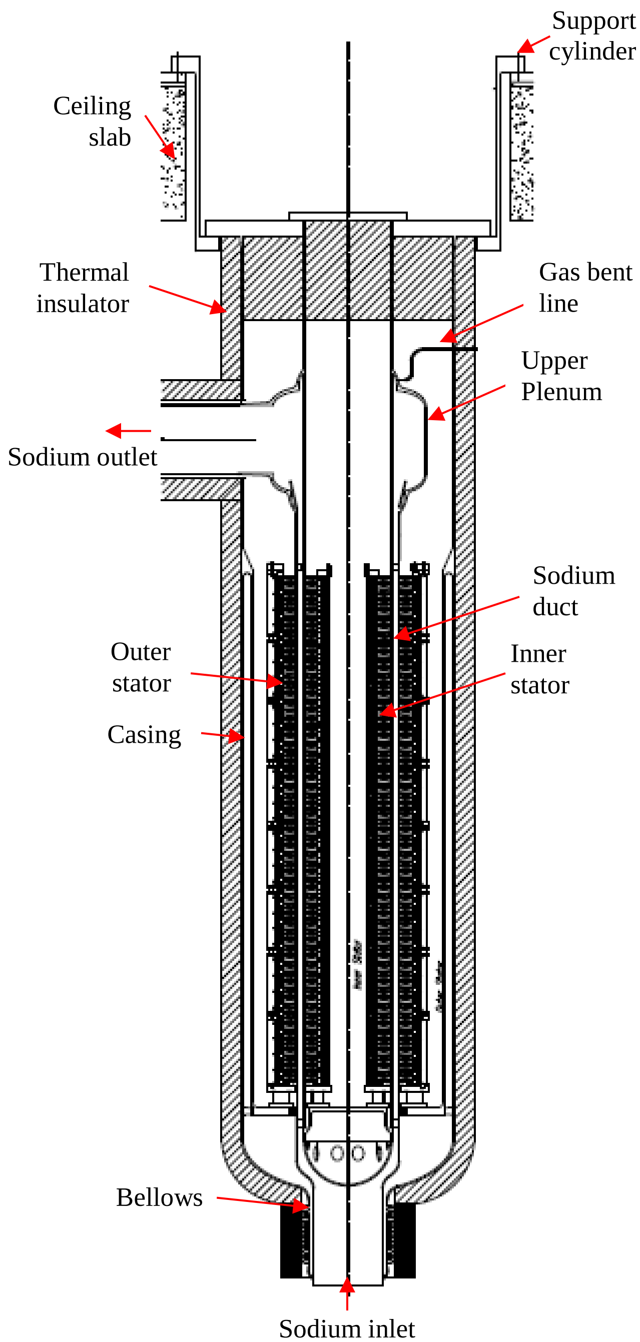

FIG.9. Conceptual structure design (Draft)

V. *Experimental model for the development of EMP*

(1) Theoretical analysis

There has been much research on the development of the numerical model describing the performance of an annular linear induction pumps (ALIP) and magnetohydrodynamic (MHD) analysis by CEA [3]. The main purpose of this theoretical analysis gets better understanding of this type of pump and to quantify any additional effects which influence both the pump efficiency and operation. Among such effects, there are the so-called instabilities due to various phenomena such as the entry or end effects, the internal three dimensional flows, and turbulence generated by the magnetic field heterogeneity.

The numerical model bases are first presented theoretically in the form of a coupled non-linear MHD system (Navier-Stokes and Maxwell equations) with appropriate boundary conditions, which gives an analytical expression as reference. Results of the numerical simulations permit to identify the MHD phenomena involved in the process for different operation parameters such as electric supply (current and frequency). Also the pressure developed by the pump is exploited, so that performance points have been plotted in terms of P-Q curve and evaluated according to electromagnetic pumps (EPM) theory of stability regimes. It is necessary for these results of the numerical model to be validated by an experiment.

(2) Facility for the experimental validation

For the validation of numerical simulations, EMP experimental model was started the details design by CEA in 2012 [2]. The experimental EMP facility PEMDYN was commissioned on October 2015 in CEA CADARACHE. PEMDYN consists on a middle-size annular EMP for the liquid metal sodium, sodium storage tank, sodium auxiliary circuit, sodium surge tank, oil cooling circuit, Na/oil heat exchanger and ball valve. The specifications of PEMDYN facility are shown in Table.3. And, the overview of PEMDYN facility is shown in FIG.10.

Table.3: The specifications of PEMDYN facility

Items	Values
Sodium flow rate	0 ~ 1500m3/h
Sodium pressure range	0.001~10 bars
Using operating temperature	115 ~ 270°C
Sodium volume in the circuit	464 liters
Oil pressure range	0.001~10 bars
Oil circuit maximum temperature	220°C

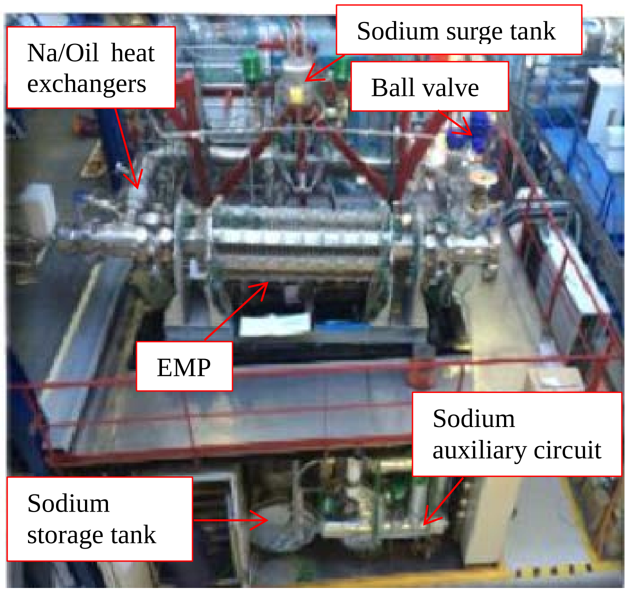

FIG.10. Overview of the PEMDYN facility

PEMDYM EMP and facilities are cooled by the organic oil. Therefore, sodium / oil heat exchanger is requires. Ball valve changes the pressure drop in the circuit, and acquires P-Q curve by the flow rate changing with it.

The principal components of PEMDYM EMP are 36 coils, 8 yokes, the magnetic inner core, power supply unit and the frame. In addition, it has any instruments for the parameter as the following; Dynamic pressure, Static pressure, Ultrasonic Doppler Velocimetry (UDV), Field distortion speed, Vibration and temperature. Magnetic field measurements have been performed on the whole length of the pumping duct (about 2.5 m) every 5 mm on 11 azimuthal positions. Measurements have been performed with a stick equipped with 9 Hall-effect sensors in order to measure the 3 components of the field (radial-Br, axial-Bz, and azimuthal-Bφ) on 3 different radial positions inside the duct (outer, mid, inner) for different azimuthal positions. The specifications of PEMDYN EMP are shown in Table.4. And, the overview of PEMDYN EMP is shown in FIG.11.

Table.4: The specifications of PEMDYN EMP

Items	Values
Maximum sodium flow rate	1450m3/h
Sodium velocity	10 m/s
Active length	2.5 m
Gap thickness	50mm
Frequency	5 ~ 25 Hz
Maximum power	325kW
Operating temperature	115 ~ 200°C

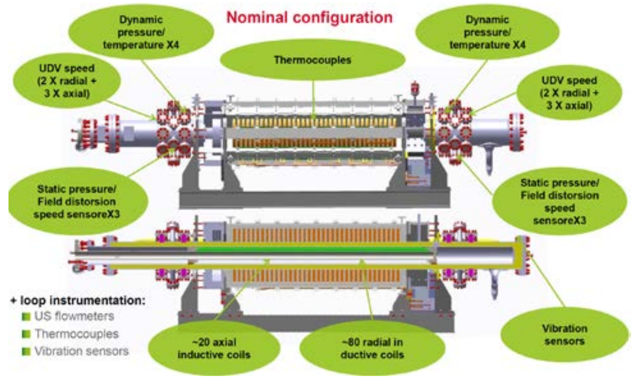

FIG.11. Overview of the PEMDYN EMP

VI. Conclusion

CEA and TOSHIBA Corporation agreed for carrying out a joint work program on the design and development of EMP for ASTRID intermediate sodium loop from 2012 to 2016. In this joint work program, the work necessary for a conceptual design of EMP were carried out by CEA and TOSHIBA. These conceptual design results provides a good confidence for the main characteristics and the feasibility of EMP for ASTRID intermediate sodium loop.

Theoritical and experimental investigations are currently in progress for the purpose of improving the numerical tools by the CEA. That is necessary to confirm characterisation of the instability phenomena and their impact on the EMP performance.

In parallel, EMP conceptual design studies for ASTRID are ongoing by TOSHIBA. An electromagnetism design to satisfy the require from a secondly loop design was considered and key specifications for the stator were decided: dimensions, electric current, voltage, frequency, efficiency... Furthermore, with electromagnetic fluid analysis, P-Q characteristic and the magnetic force distributions of the EMP were confirmed.

In addition, the following items are ongoing by TOSHIBA: the thermal analysis and thermal stress analyses, the aseismic analysis and the mechanical interfaces, the definition of the power supply unit, the instrumentation and the remote control procedure.

This program is aiming to consolidate the ASTRID EMP conceptual design by 2017 and to support the design option choice for the ASTRID basic design.

NOMENCLATURE

ALIP Annular linear induction pump
ASTRID Advanced Sodium Technological Reactor for Industrial Demonstration
CEA Commissariat à l'Energie Atomique et aux Energies Alternatives
CFD Computational Fluid Dynamics
EFR European Fast Reactor
EMP Electro Magnetic Pumps
FBR Fast Breeder Reactor
GENIV Generation IV initiative
IHX Intermediate Heat Exchanger
EMP Large Electro Magnetic Pump
MHD Magneto Hydro Dynamics
SFR Sodium-cooled Fast Reactor
SG Steam Generator
SGHE Sodium Gas Heat Exchanger
SWAR Sodium-Water-Air Reaction
SWR Sodium-Water Reaction

REFERENCES

[1] F. Gauché; The French Prototype of 4th Generation Reactor: ASTRID; Annual meeting on nuclear technology, Berlin, May 17&18th; 2011.

[2] F. Rey *et al*. ; Development of large flow ALIP EMP for application in ASTRID sodium cooled fast reactor and future power plant reactors, 8th PAMIR International Conference, Vol. 1 paper B2_18, p. 551-556, September 5-9, 2011, Borgo, C

[3] E.Martin Lopez, Y. Delannoy, F. Benoit, R. Martinie, S. Vitry NUMERICAL AND EXPERIMENTAL VALIDATION OF THE PERFORMANCE OF AN ELECTROMAGNETIC PUMP FOR A SODIUM FAST REACTOR, 2017 International Congress on Advances in Nuclear Power Plants

[4] G. Laffont *et al*. ; Large capacity EMP design for application in ASTRID sodium cooled fast reactor, FR13, P.199-263, IEAE-CN-199, Paris, France, 4-7 March 2013

[5] W. Kwant *et al*.; In-Sodium testing and performance of a 43.5m^3/min electromagnetic pump for LMR application, 5th International Conference on Nuclear Engineering, ICONE 5-2553, May 25-30, Nice, France.

[6] H. Ota *et al.*; Development of 160m^3/min Large Capacity Sodium-Immersed Self-Cooled Electromagnetic Pump; Journal of Science and technology, Vol. 41,N°4, p.511-523, April 2004. Paper CN-199-126

[7] S. Vitry, L. Goldsteins, C. Biscarrat, F. Benoit, S. Madeleine, F. Dechelette, O. Gastaldi, Experimental and numerical analysis of magnetic field spatial measurements inside an electromagnetic pump channel duct, 10TH PAMIR International Conference Fundamental and Applied MHD, 2016

[8] L. Ayrault, D. Cambet-Petit-Jean, M. Fauré, S. Albaladejo, J.Ph. Jeannot, A High flowrate electromagnetic pump for Astrid in test: design, conception and start-up of a new facility devoted to the qualification of performances and MHD phenomena, 10TH PAMIR International Conference Fundamental and Applied MHD, 2016