# *Residual thermal deformation of the gas-turbine engine exhaust assembly*

**- The analyzed problem was reported during acceptance tests, when the turbine performance deteriorated after a number of starts.**

**- Part of the deterioration is due to the exhaust assembly deformation.**

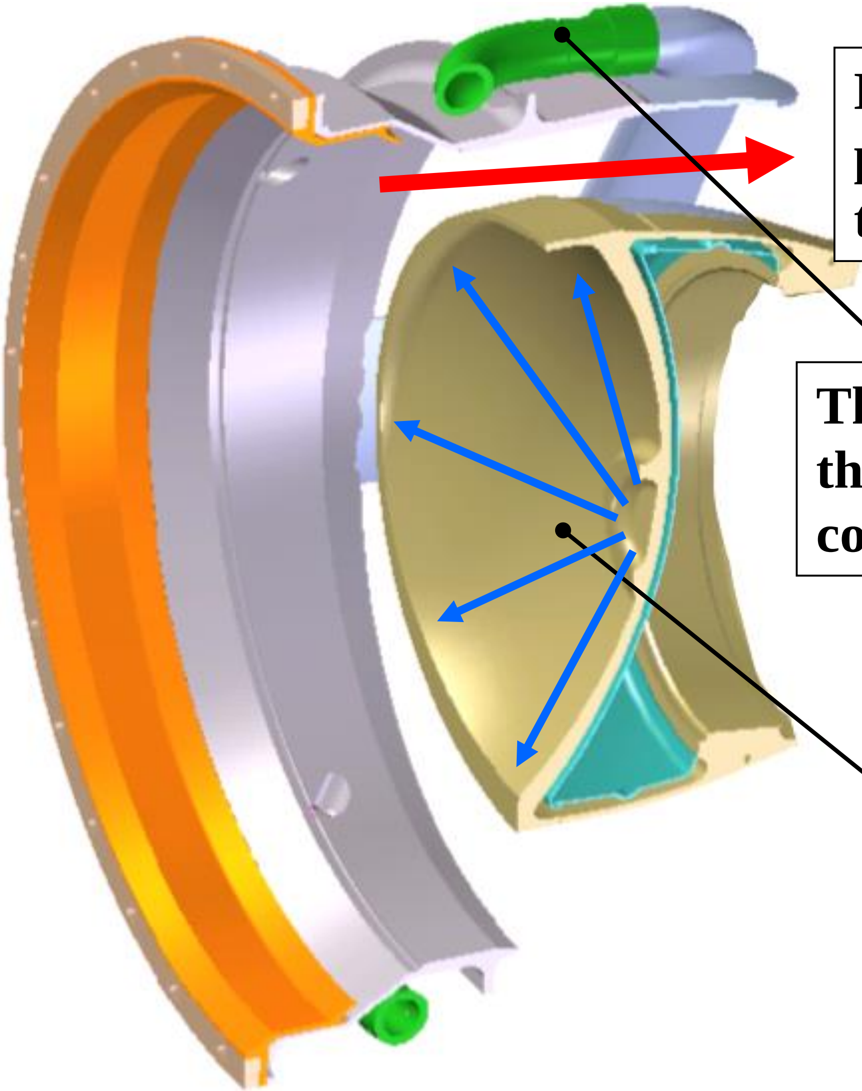
**- Usually, after a few starts turbine performance stabilized.**

**- Obviously, the residual deformation is due to multicyclic thermal load, because of plastic behavior of the exhaust assembly material.**

**- The engine operation cycle consists of starting, engine operation and shutting down, which produces a non-uniform thermal cyclic load in the exhaust assembly.**

**- After the next operating cycle the exhaust assembly does not return to the same deformed original configuration because of the kinematic (cyclic) plasticity material behavior.**

# The thermal load on the exhaust assembly



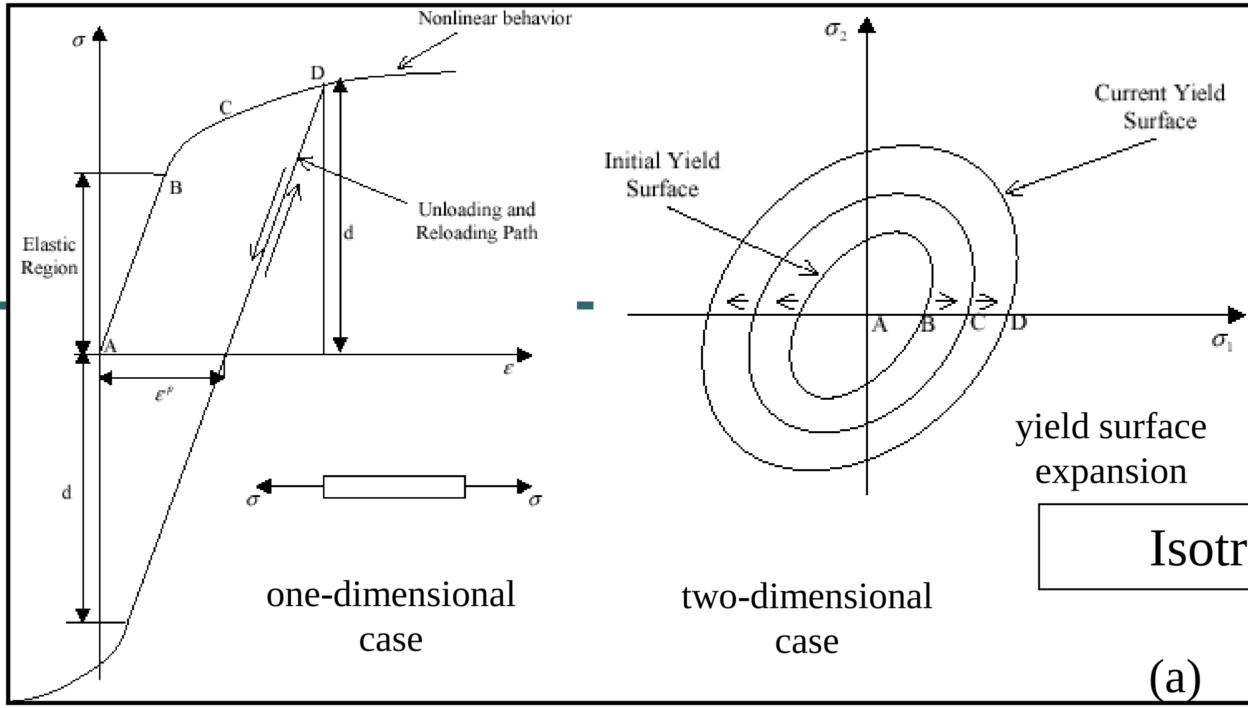
Non-uniformly distributed in peripheral direction high temperature exhaust gases

The outer surfaces are exposed to the outer environment free convection

The frontal surface is exposed to the turbine cooling air

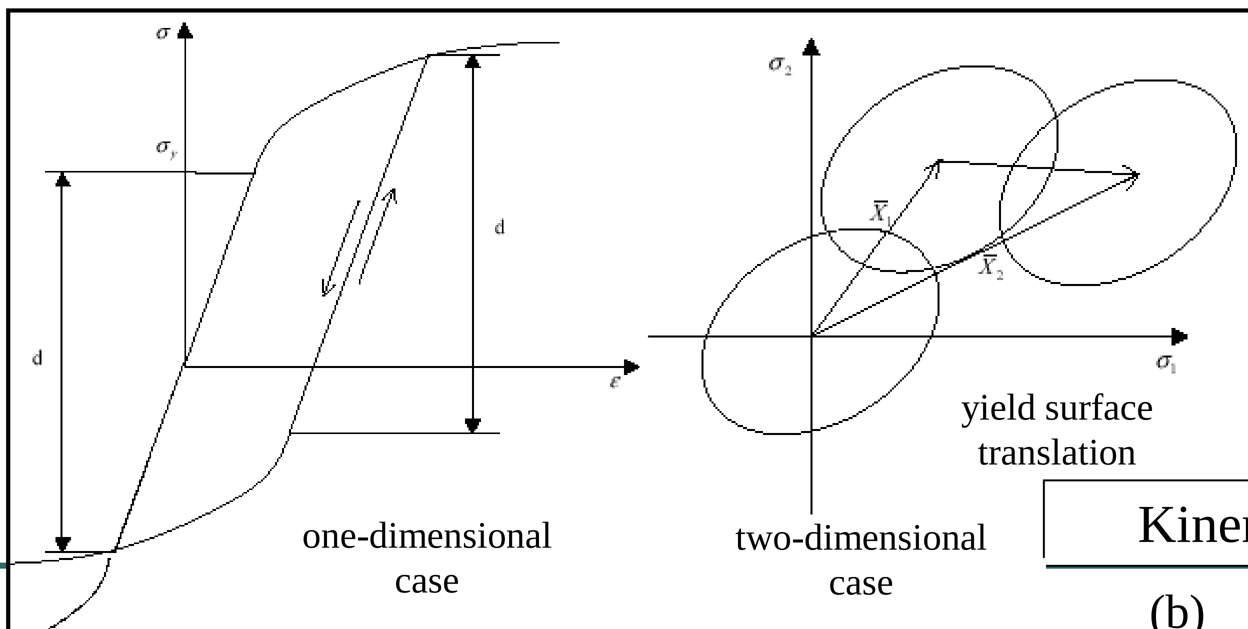
# Isotropic and kinematic hardening plasticity

- **Isotropic hardening accounts for the change in size of the yield surface.**
- **Kinematic hardening, on the other hand, accounts for the translation of the yield surface.**
- **Combined hardening, on the other hand, accounts for both aforementioned effects.**



(a)

# Isotropic plasticity

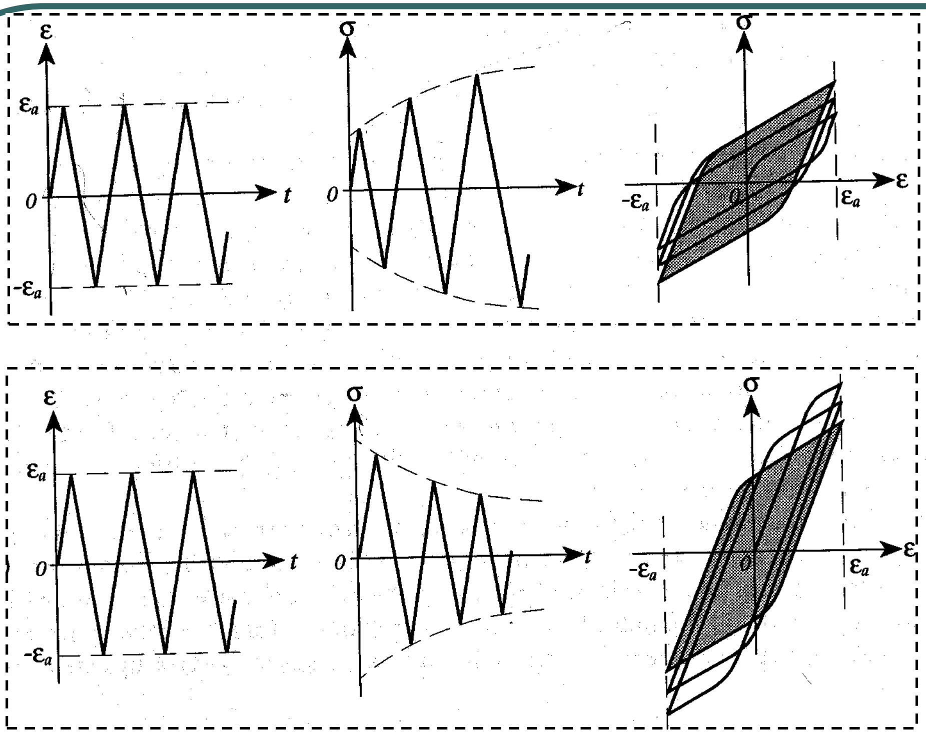


(b)

# Kinematic plasticity

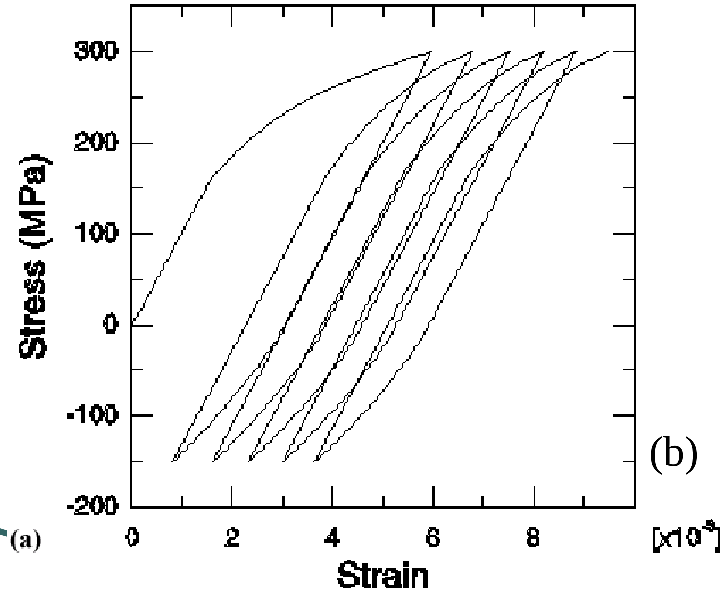
# Isotropic and kinematic hardening plasticity

- **When a specimen undergoes loading and unloading for a number of cycles the stress-strain relationship takes an hysteresis loop form.**
- **Cyclic hardening or cyclic softening occurs if the subsequent loading-unloading hysteresis loops tend to converge.**
- **Non-proportional loading occurs when the relation between stress components increment is not a constant.**
- **Ratcheting is the accumulation of the plastic strain cycle-by-cycle for some stress amplitude with a non-zero mean stress.**




(a)

- **An illustration of the cyclic hardening, cyclic softening and ratcheting effects in kinematic plasticity**




(b)

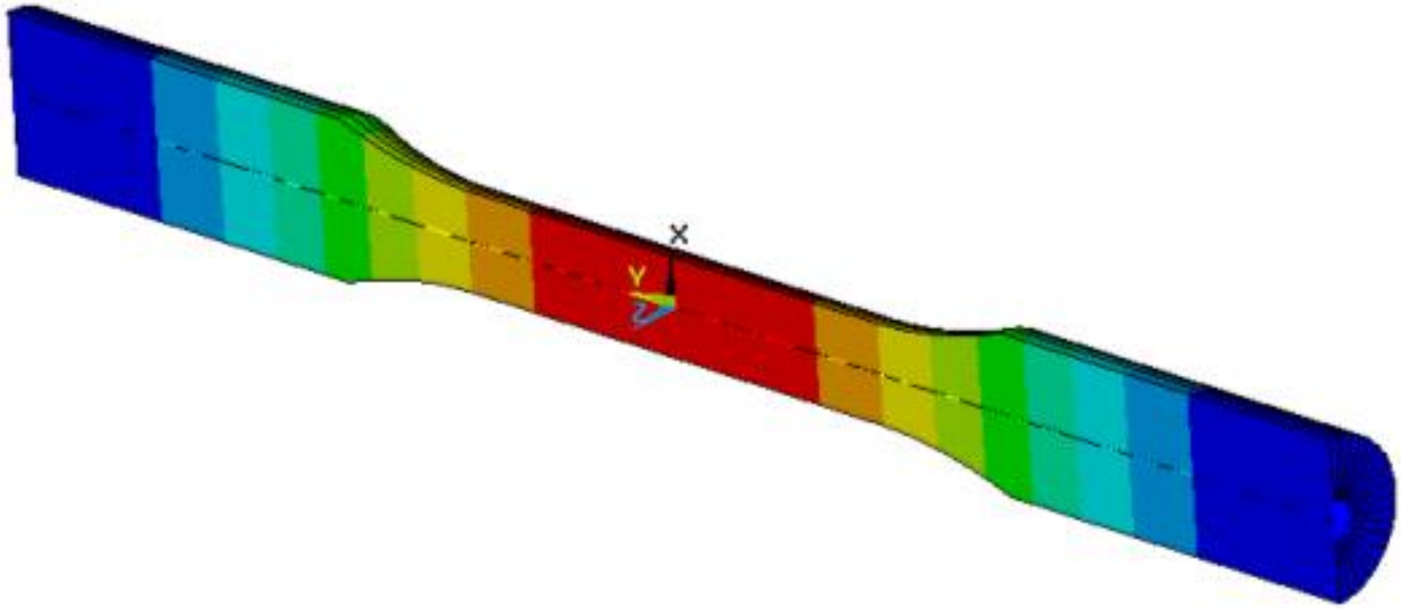
# Isotropic and kinematic hardening plasticity

A well developed material kinematic plasticity model must include a quantified description of:

- the correct non-linearity of stress-strain loop under cyclically stable condition
- the Bauschinger effect
- the cyclic hardening/softening effects
- the ratcheting effect

**The chosen cyclic plasticity model was checked on the standard tensile test specimen fixed at both ends.**

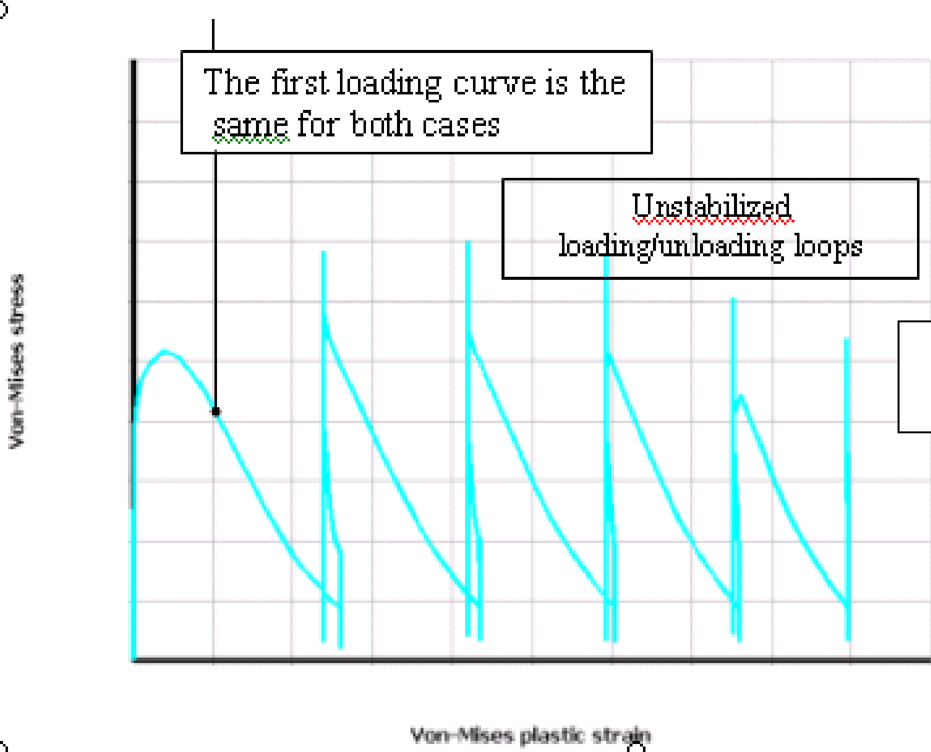
**The specimen is loaded by the cyclic non-uniformly distributed thermal load.**



(a)


**Kinematic plasticity case**

(b)




**Isotropic plasticity case**

- **The goal of the presented study is to decrease residual thermal deformation after machine cooling (end of the cycle).**

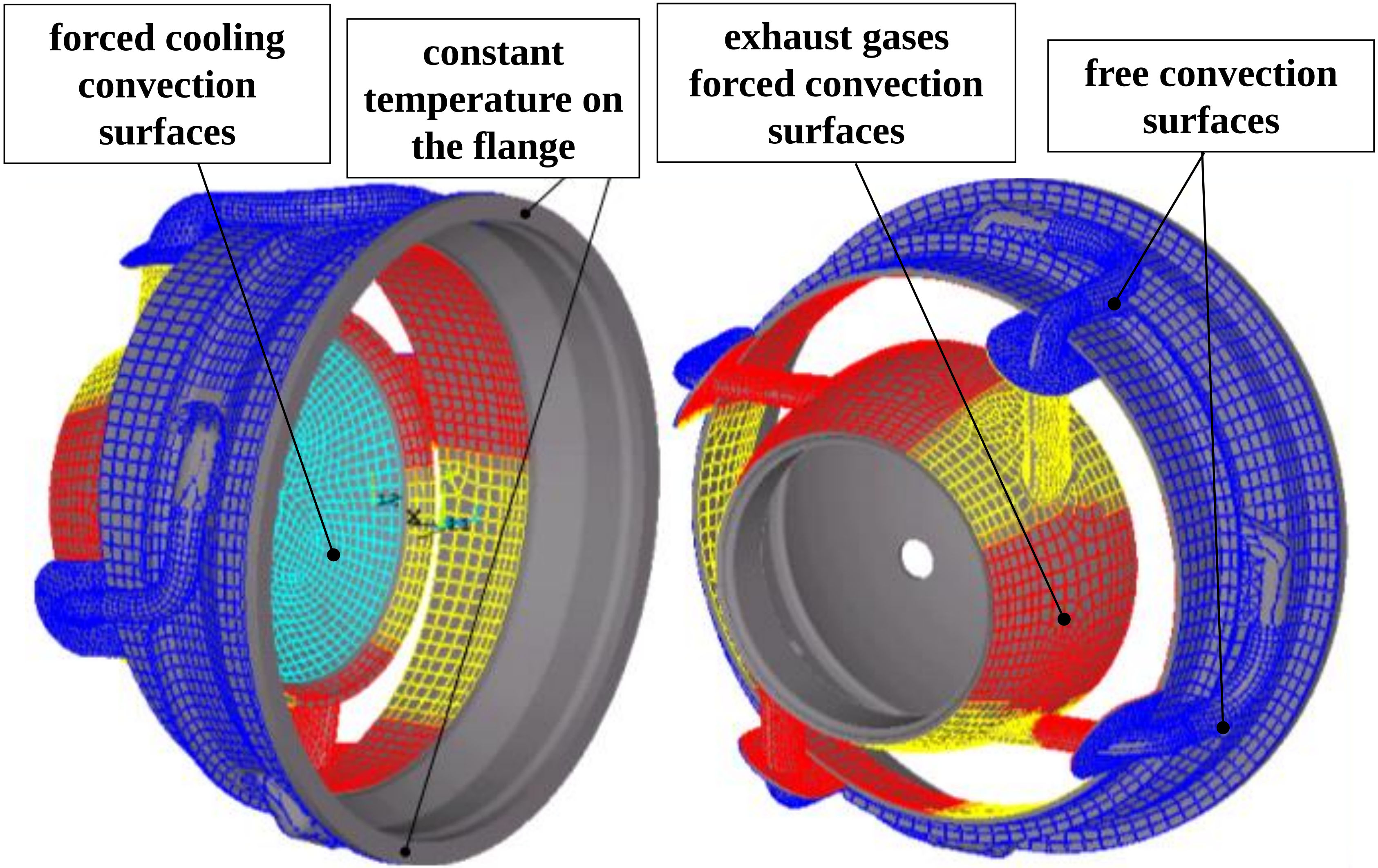
- **It can be achieved by decreasing plastic deformation at the peak temperature deformed configuration.**

- **One possible way to decrease plastic deformation in our case is to remove (or weaken) the thermal load on the exhaust assembly.**

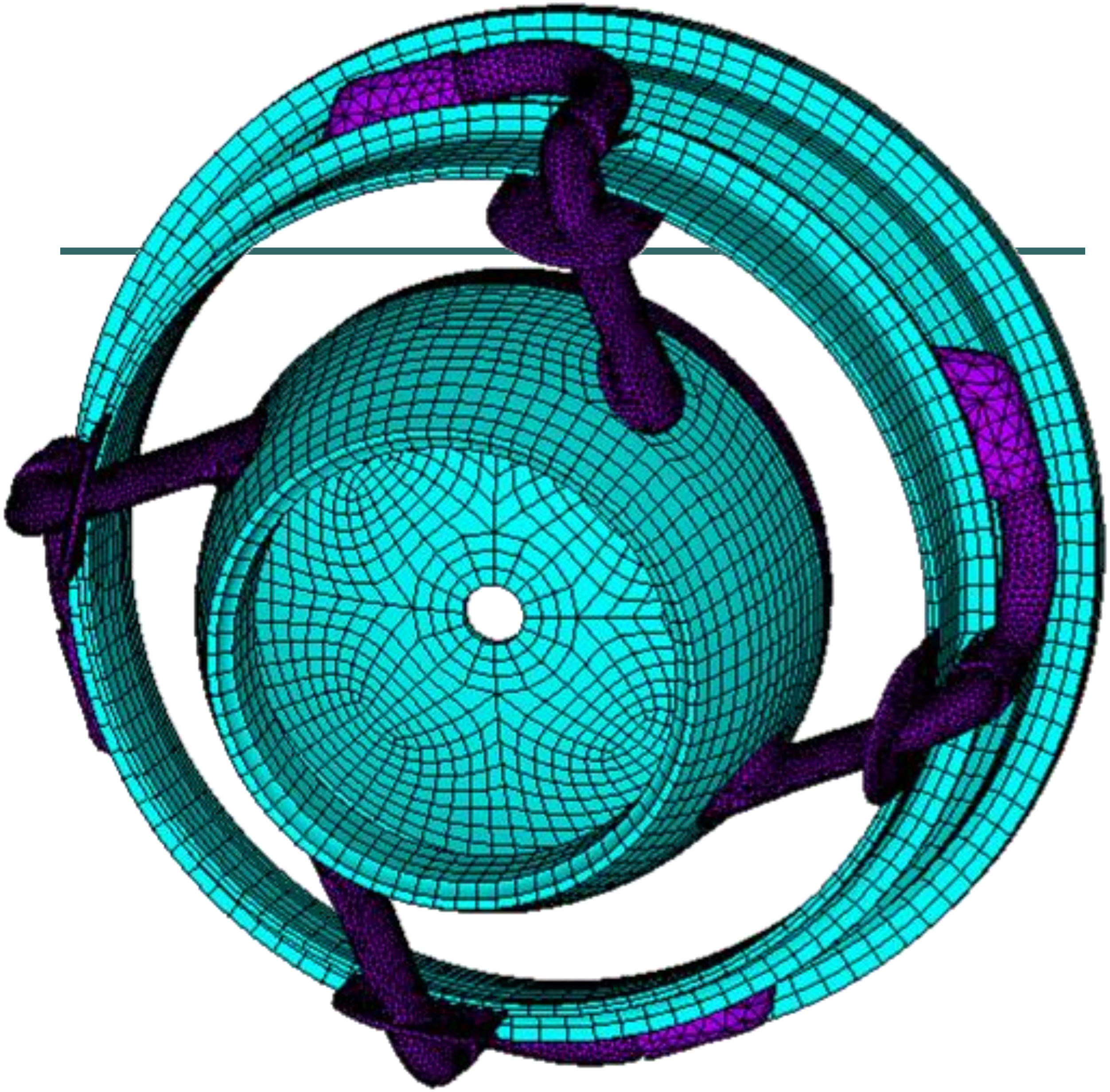
## Non-uniform cyclic thermal load is created by the following convection BC:

- **By non-uniform peripheral distribution of the high temperature exhaust gases**
- **By presence of the cooling air at the front surface**
- **By free convection at the outer surface**

# Thermal boundary condition



- **Finite Element Model of the Exhaust Assembly**



**Thermal analysis**

(to obtain steady-state temperature distribution)

↓

**Structural non-linear kinematic plasticity analysis**

(loaded with obtained temperature distribution)

↓

**Structural non-linear kinematic plasticity analysis**

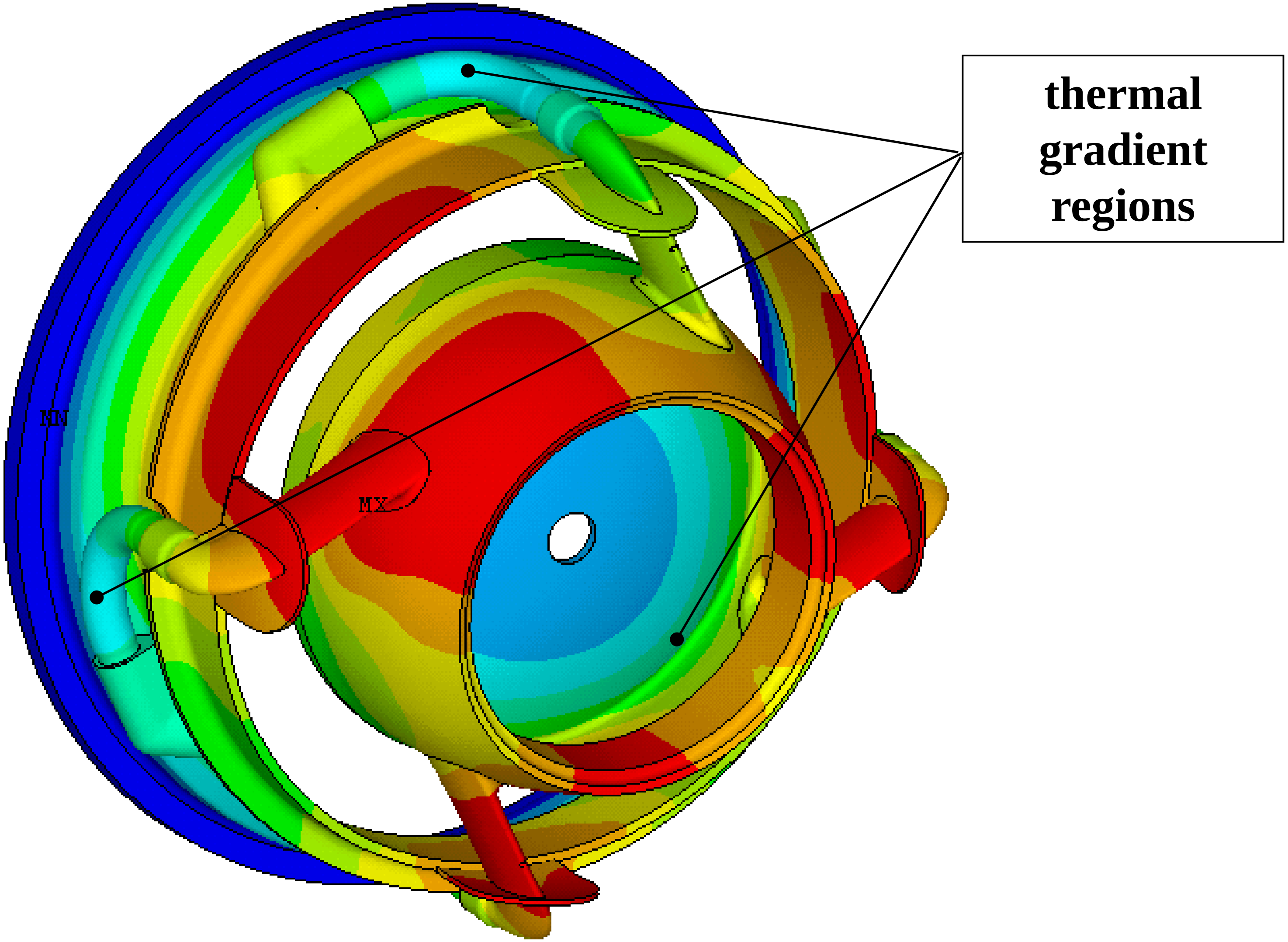
(thermal loads removed)

↓

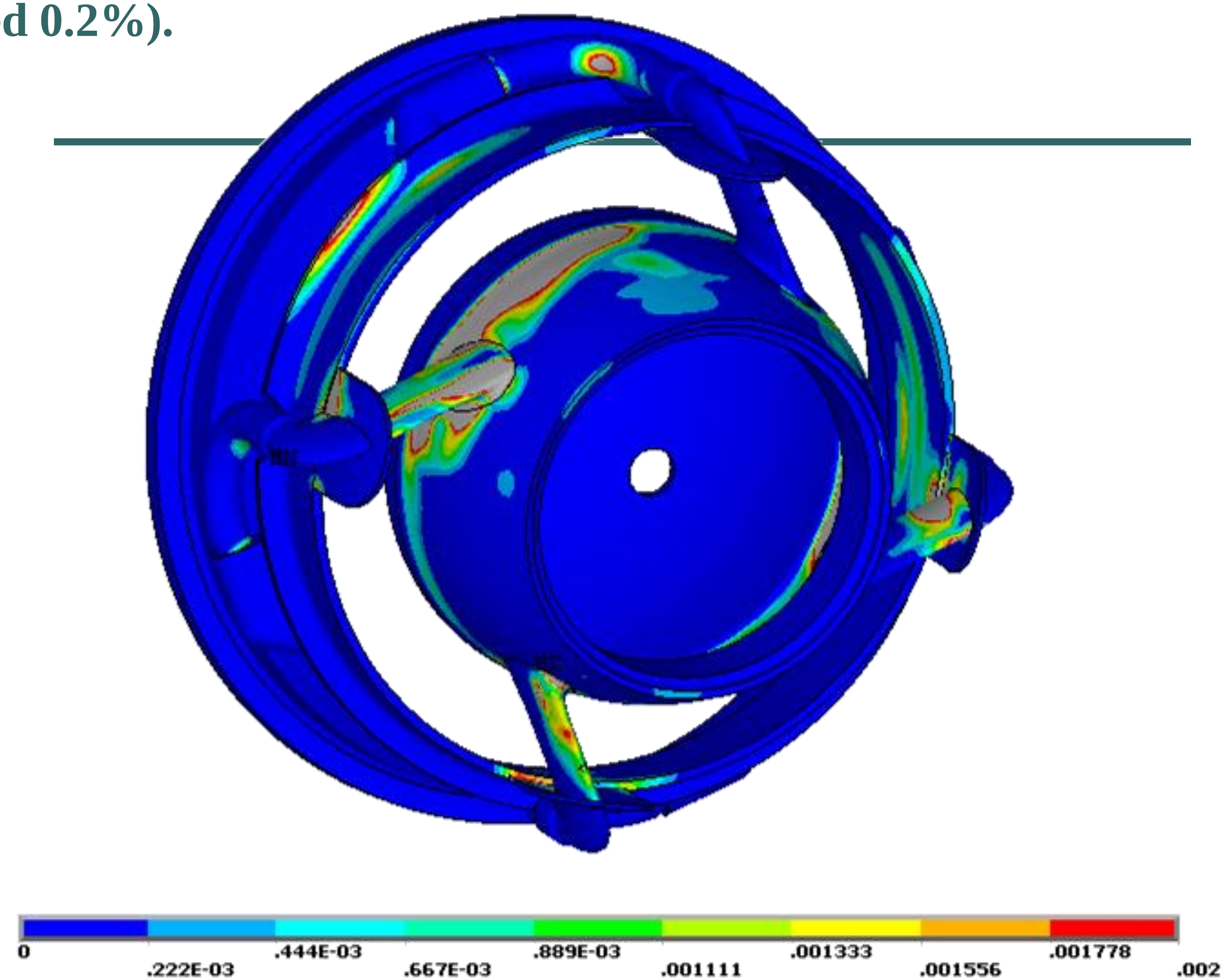
**Results:**

1. **Plastic strain at machine operation cycle**
2. **Residual deformation at machine shut-down cycle**

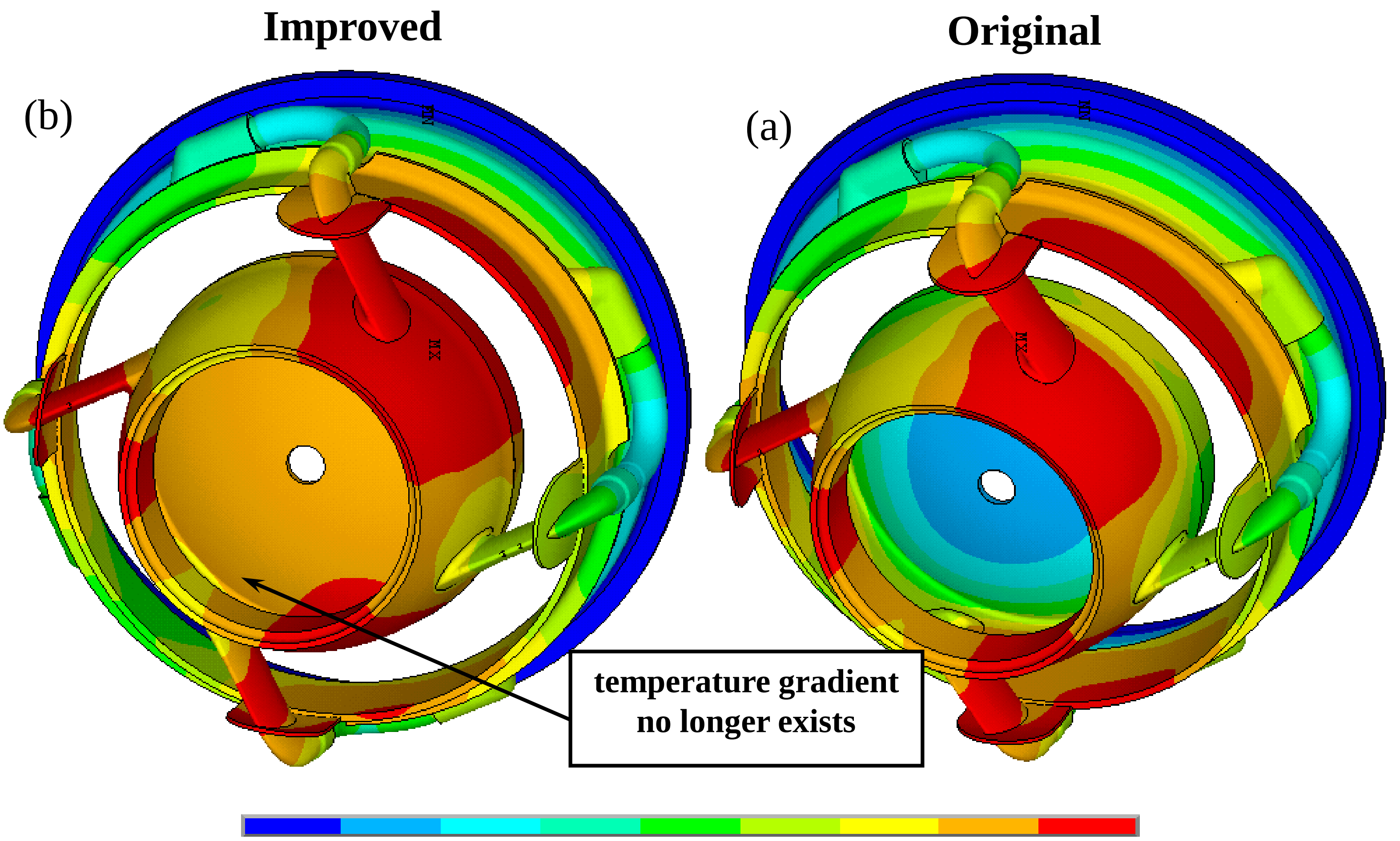
# Temperature distribution analysis results inside the exhaust assembly (existing design)



**Von-Mises plastic strain distribution at the peak temperature deformed configuration (Gray color represent the regions where plastic strain exceeded 0.2%).**

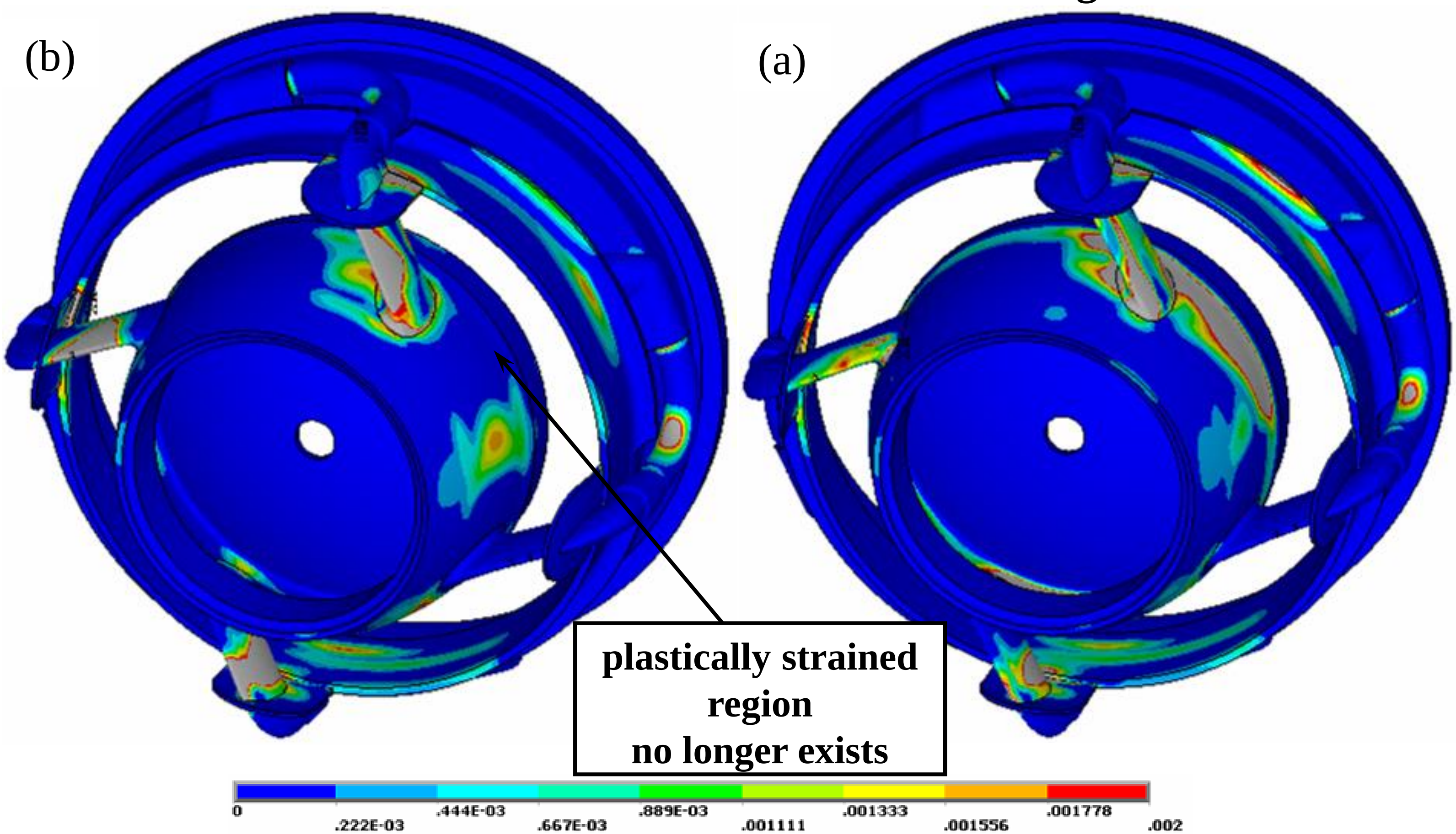


# The effect of thermal insulation adding at the front surface on nozzle temperature distribution

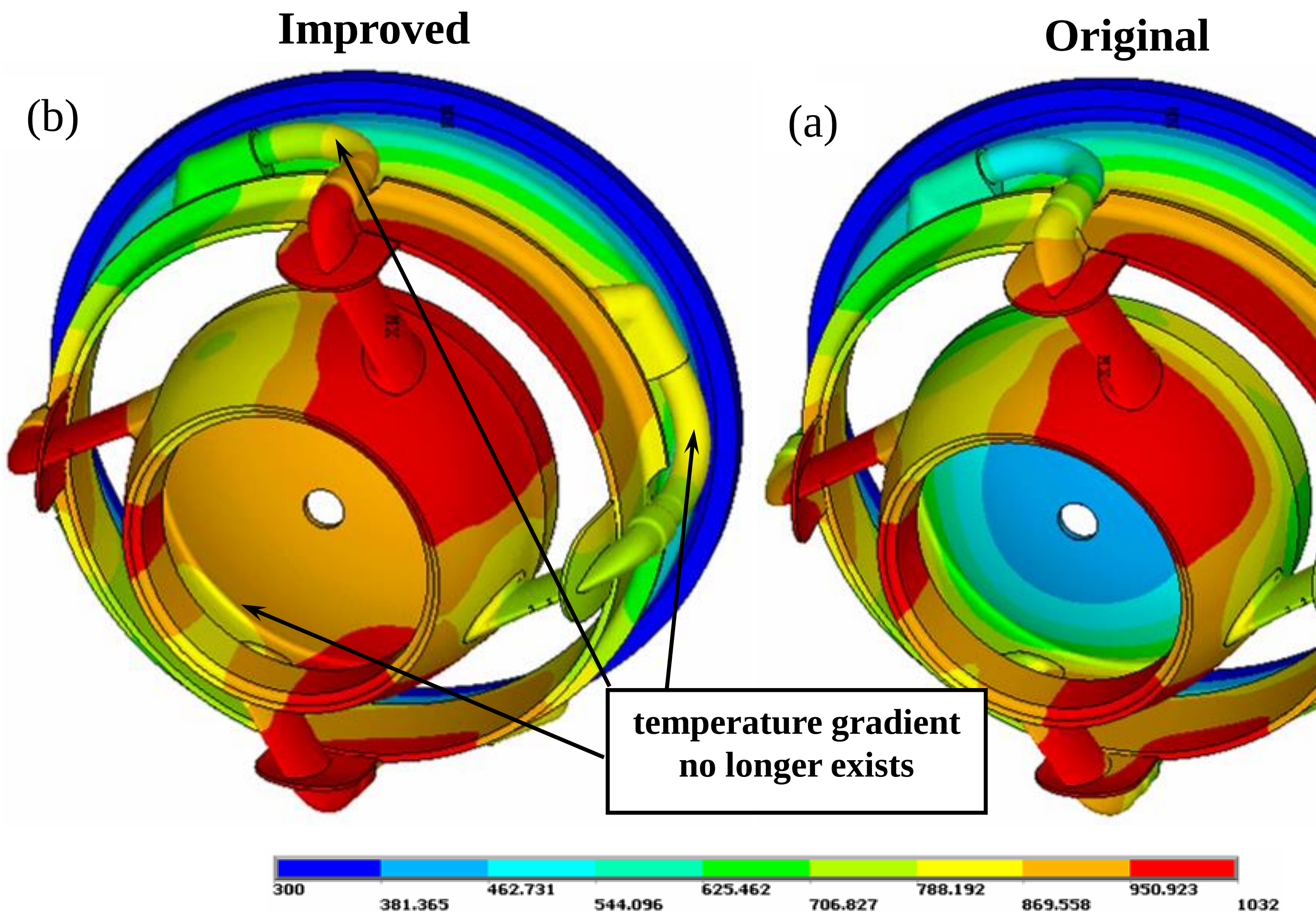


# The effect of thermal insulation at the front surface on nozzle plastic strain distribution

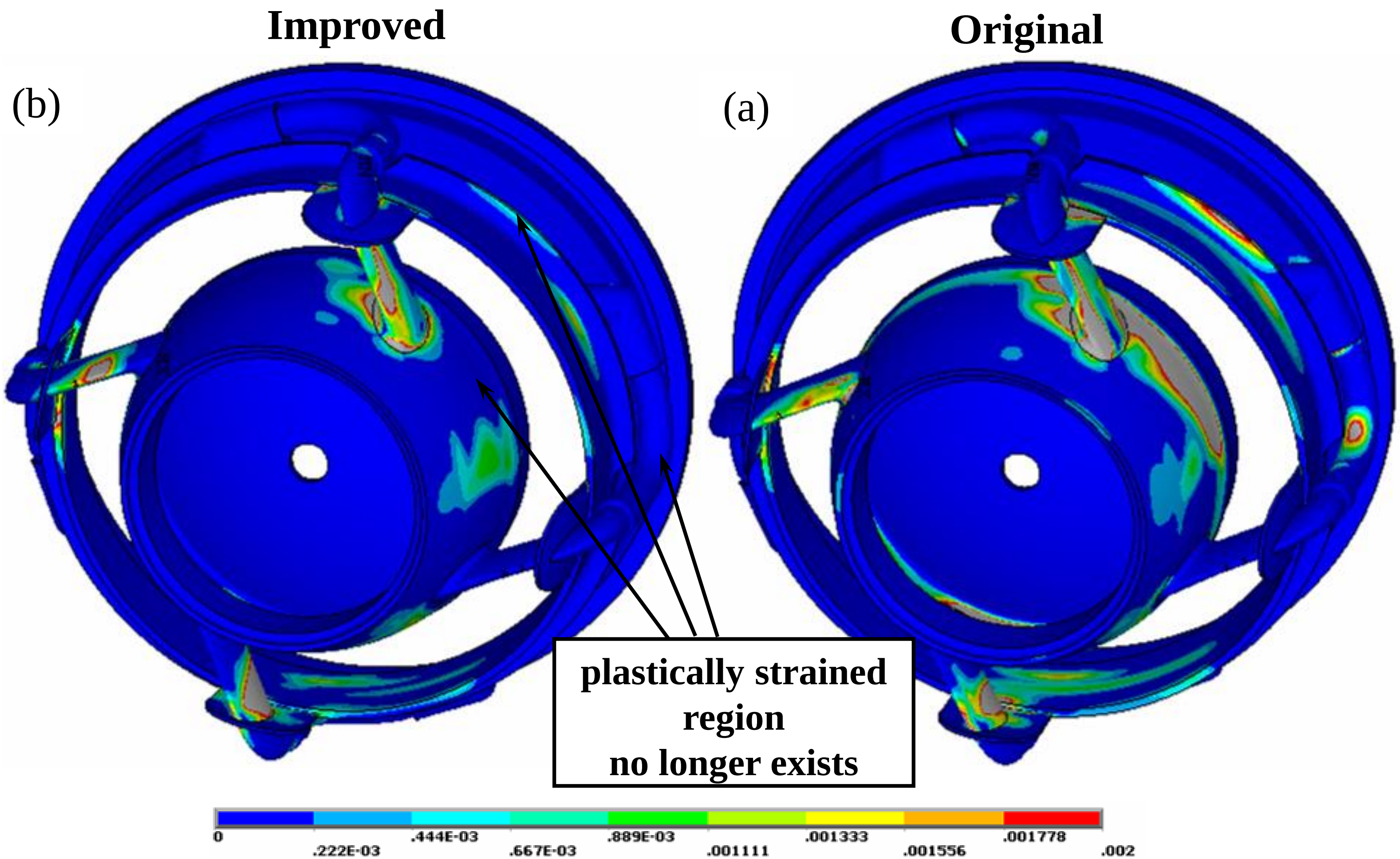
**Improved** **Original**



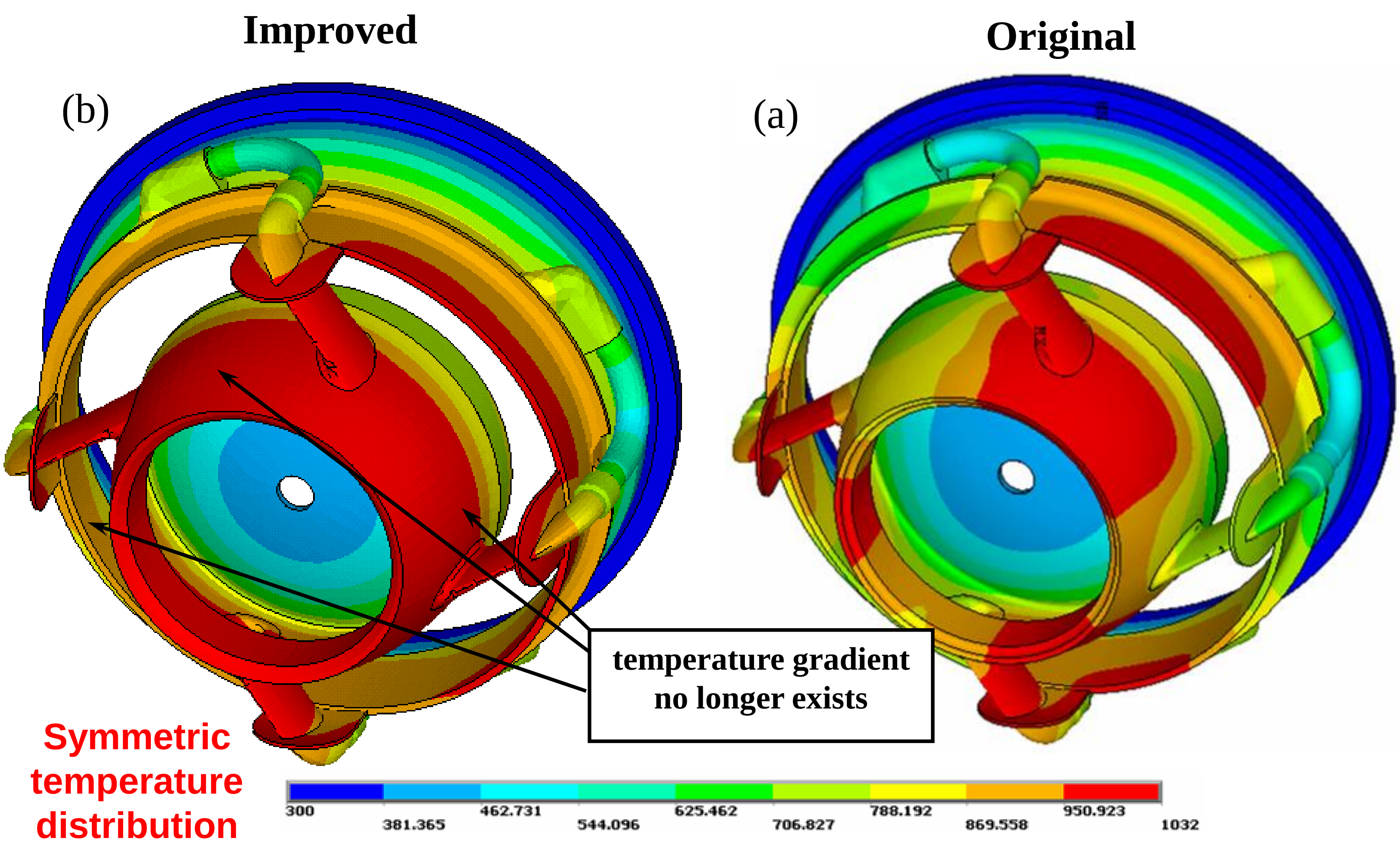
## The effect of thermal insulation adding at the front surface as well as at the outer piping on nozzle temperature distribution



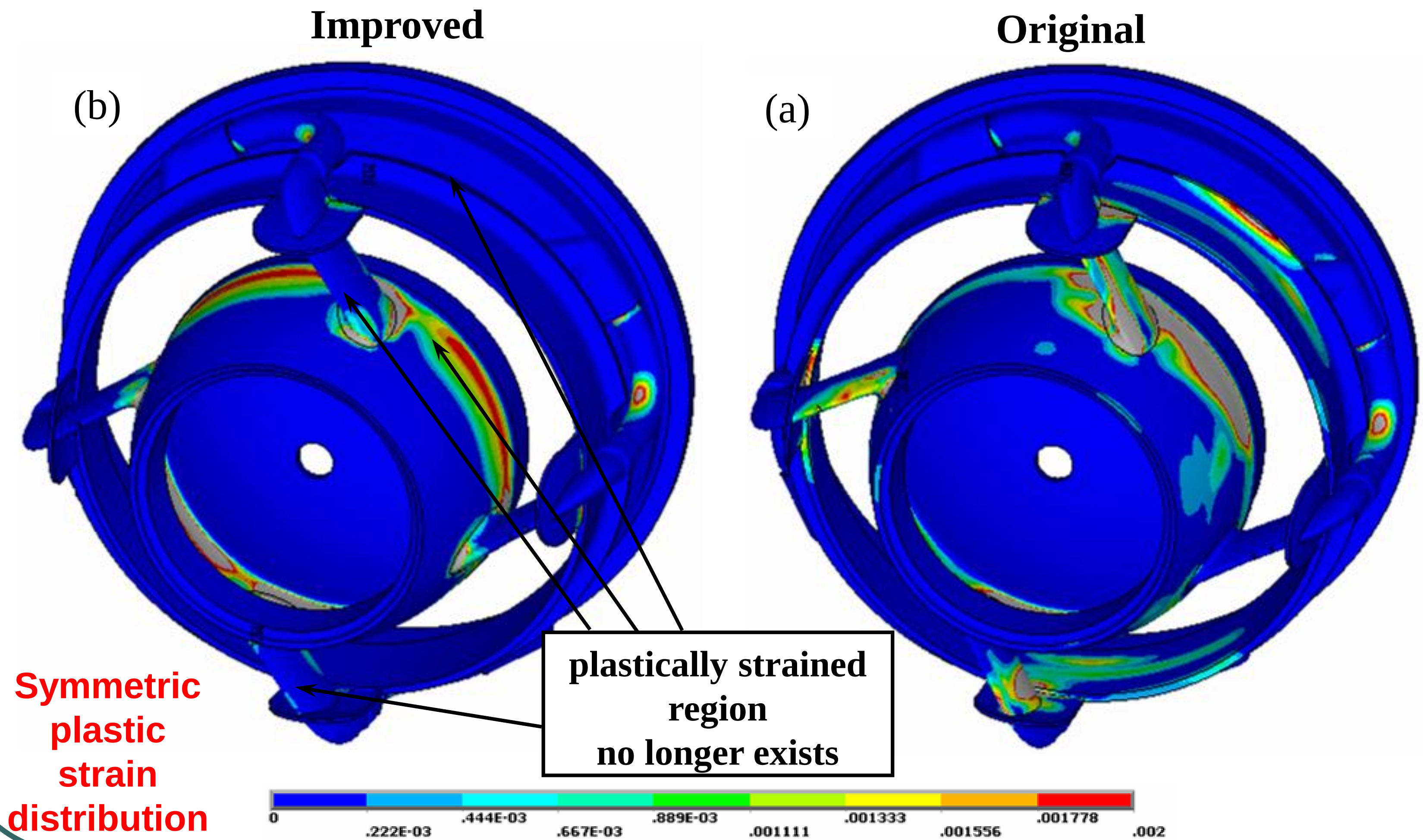
# The effect of thermal insulation at the front surface as well as at the outer piping on nozzle plastic strain distribution



## Temperature distribution analysis results inside the exhaust assembly when temperature distribution of the exhaust gases in the peripheral direction is uniform



# The effect of uniform peripheral distribution of exhaust gases on nozzle plastic strain distribution



# Analysis results:

- **Use of the thermal insulation at the front surface of the exhaust assembly decreased non-uniformity in radial deformation at the peak temperature configuration by ~8.9%.**

- **Use of the thermal insulation at the front surface of the exhaust assembly as well as at the outer region decreased non-uniformity in radial deformation at the peak temperature configuration by ~21.5%.**

## Analysis results:

- **Use of the thermal insulation at the front surface of the exhaust assembly increased non-uniformity in residual radial deformation at the cooled deformed configuration by ~15.4%.**

- **Use of the thermal insulation at the front surface of the exhaust assembly as well as at the outer region decreased non-uniformity in residual radial deformation at the cooled deformed configuration by ~30.1%.**

## Conclusions:

- **Although a thermal insulation reduces the residual deformation by 30%, some steps must be taken to reduce temperature non-uniformity of the exhaust gases.**

- **The analysis results were verified by turbine tip clearance measurement. The same level of tip clearance non-uniformity was obtained which validate the chosen approach.**